Fig. 1A

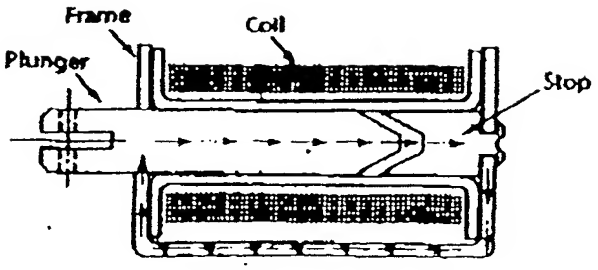


Fig. 1B

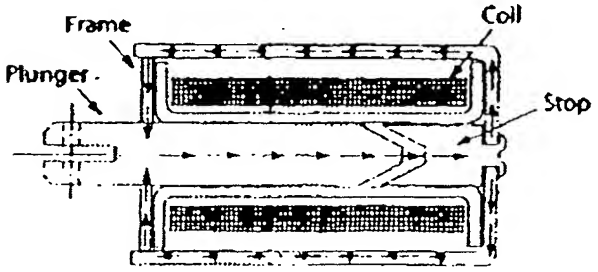
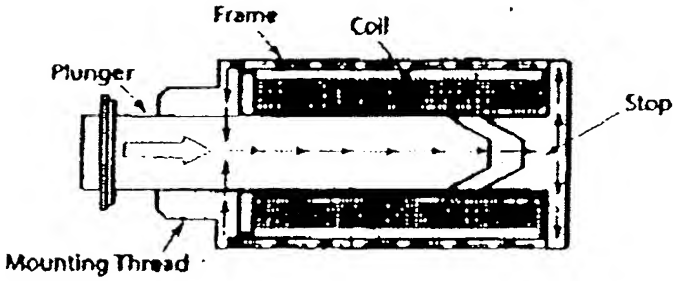


Fig. 1C



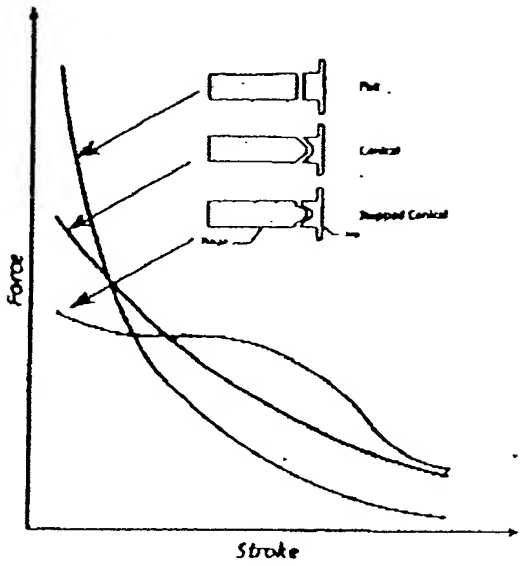


Figure 2

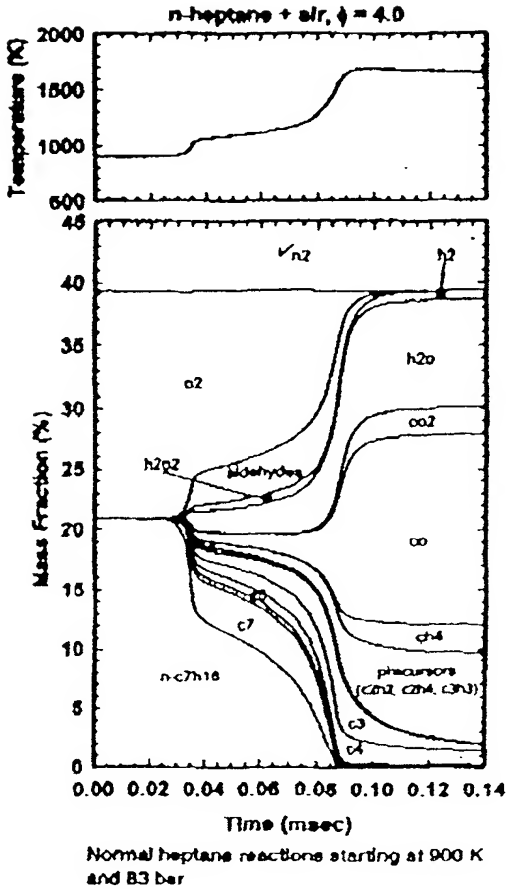

n-heptane + air, ϕ = 4.0
Temperature (K)
2000
1500
1000
600
Mass Fraction (%)
45
40
35
30
25
20
15
10
5
0
n2
h2
o2
h2o
co2
h2o2
aldehydes
co
ch4
c7
n-c7h16
precursors
(C2h2, C2h4, C3h3)
c3
c4
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14
Time (msec)
Normal heptane reactions starting at 900 K
and 83 bar

Figure 3

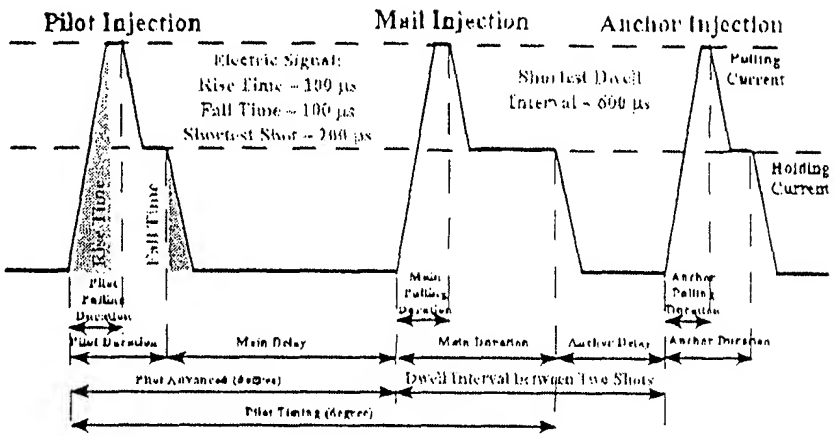
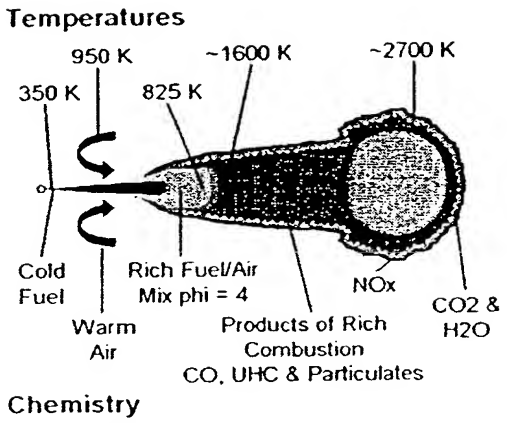

Pilot Injection
Main Injection
Anchor Injection
Electric Signal:
Rise Time = 100 μs
Fall Time = 100 μs
Shortest Shot = 200 μs
Shortest Dwell
Interval = 600 μs
Pulling
Current
Holding
Current
Rise Time
Fall Time
Pilot
Pulling
Duration
Main
Pulling
Duration
Anchor
Pulling
Duration
Pilot Duration
Main Delay
Main Duration
Anchor Delay
Anchor Duration
Pilot Advanced (degree)
Dwell Interval between Two Shots
Pilot Timing (degree)

Figure 4



Summary of fuel burning processes

Figure 5

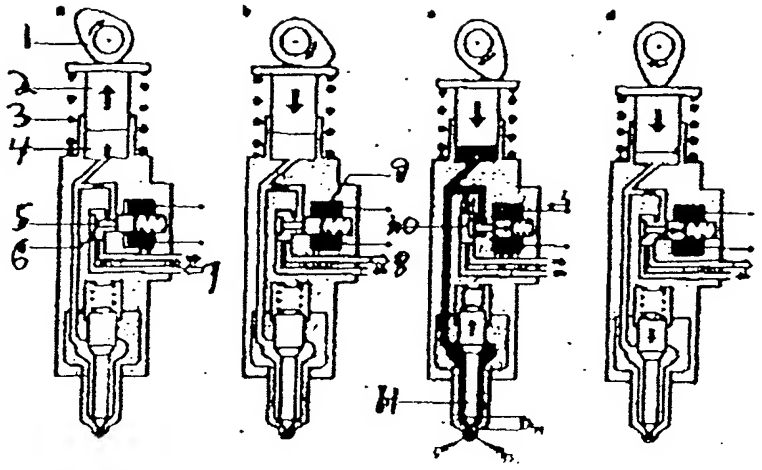


Fig. 6A Fig. 6B Fig. 6C Fig. 6D

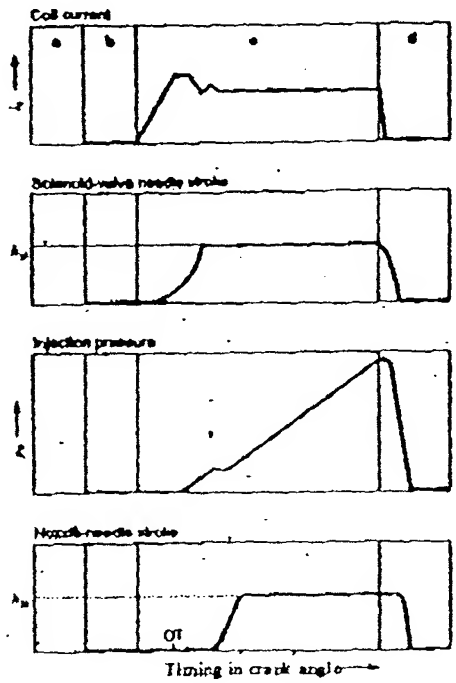


Fig. 7A

Fig. 7B

Fig. 7C

Fig. 7D

Wave Form Diagram: Operation of Fuel Injection Nozzle

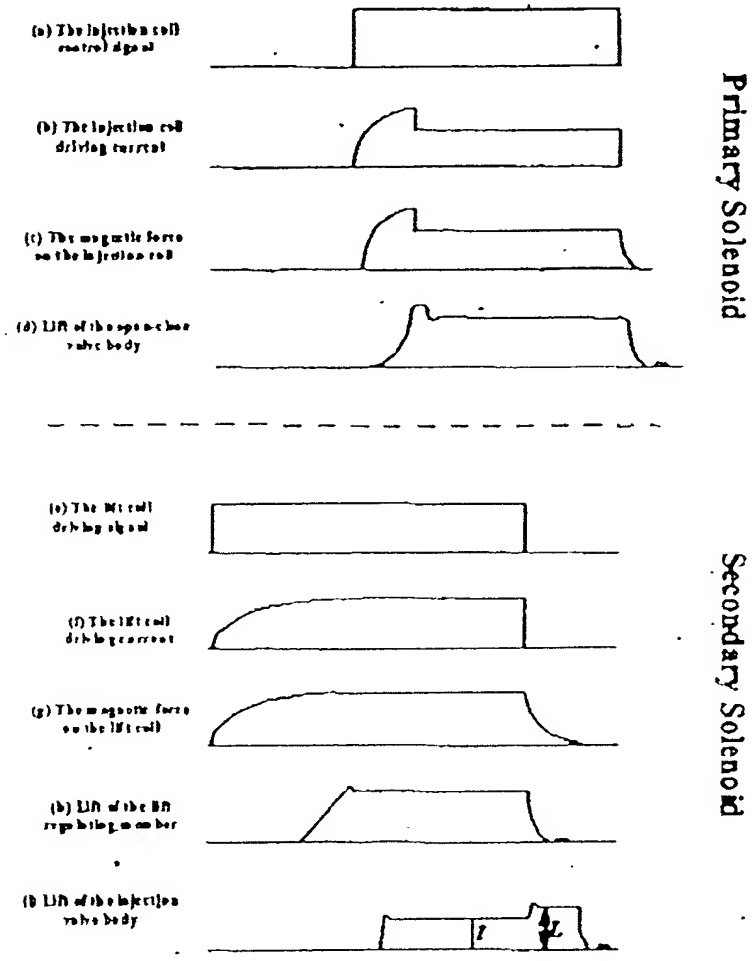


Figure 8

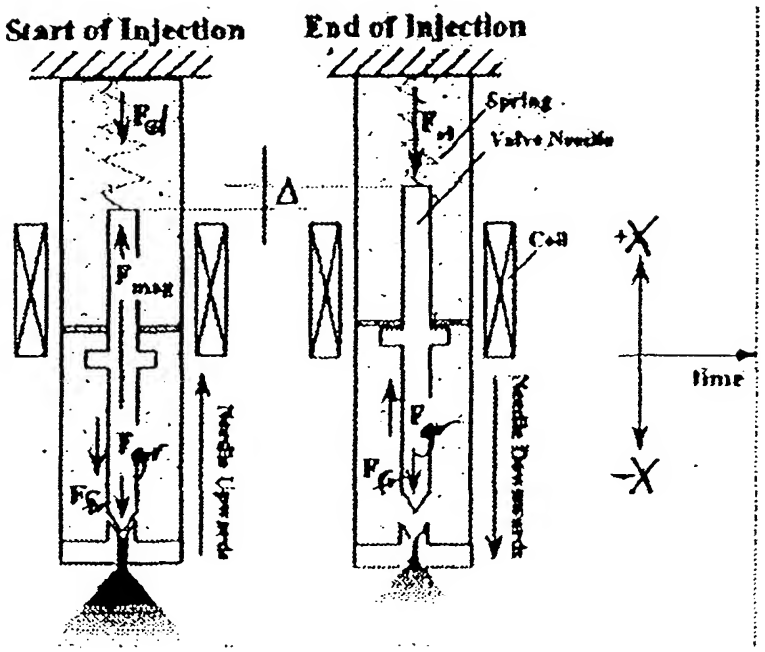

Start of Injection
End of Injection
Spring
Valve Needle
Coil
Δ
Time

Figure 9

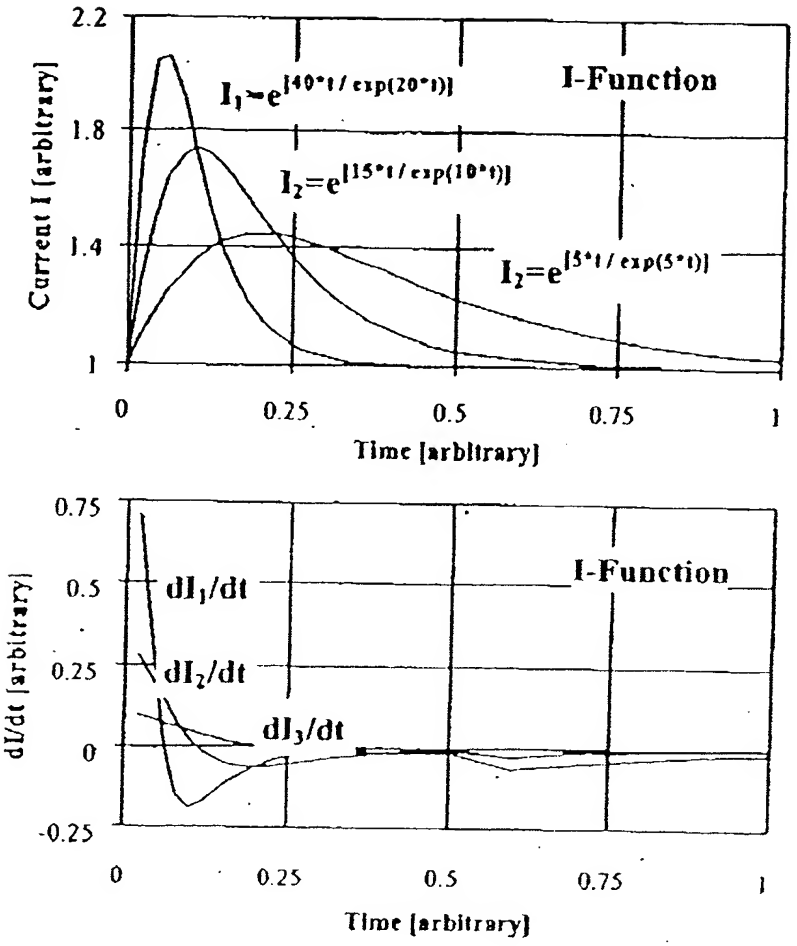

2.2
1.8
1.4
1
Current I [arbitrary]
I-Function
$I_1=e^{[40*t/\exp(20*t)]}$
$I_2=e^{[15*t/\exp(10*t)]}$
$I_2=e^{[5*t/\exp(5*t)]}$
0
0.25
0.5
0.75
1
Time [arbitrary]
0.75
0.5
0.25
0
-0.25
dI/dt [arbitrary]
I-Function
dI_1/dt
dI_2/dt
dI_3/dt
0
0.25
0.5
0.75
1
Time [arbitrary]

Figure 10

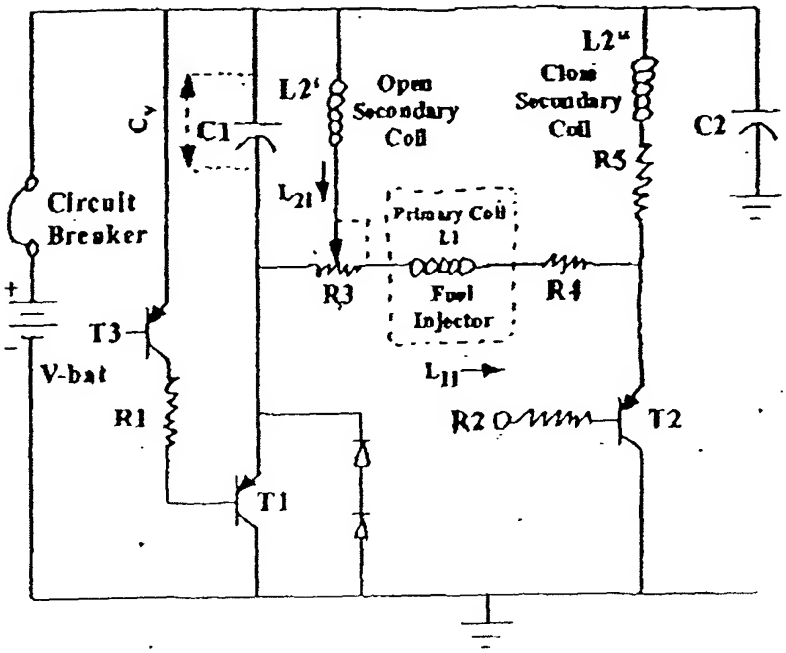


Fig. 11A

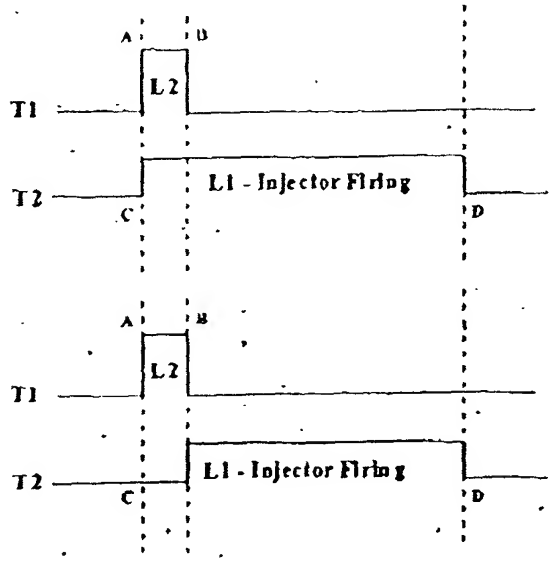


Fig. 11B

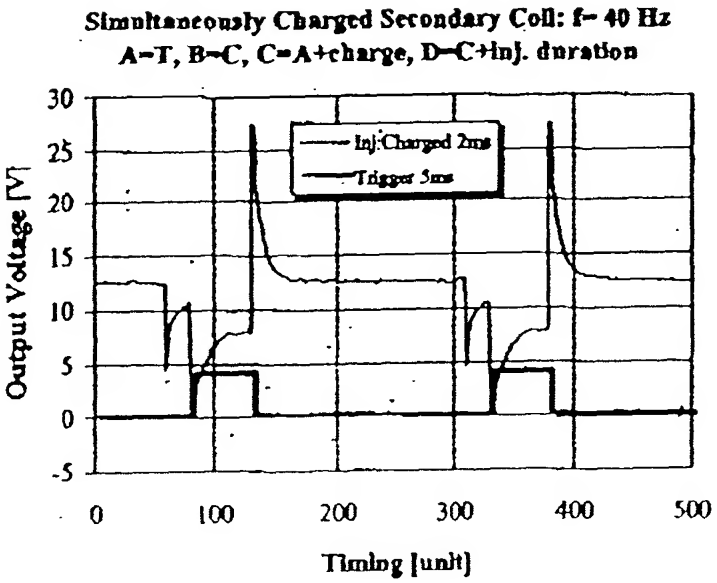


Fig. 12A

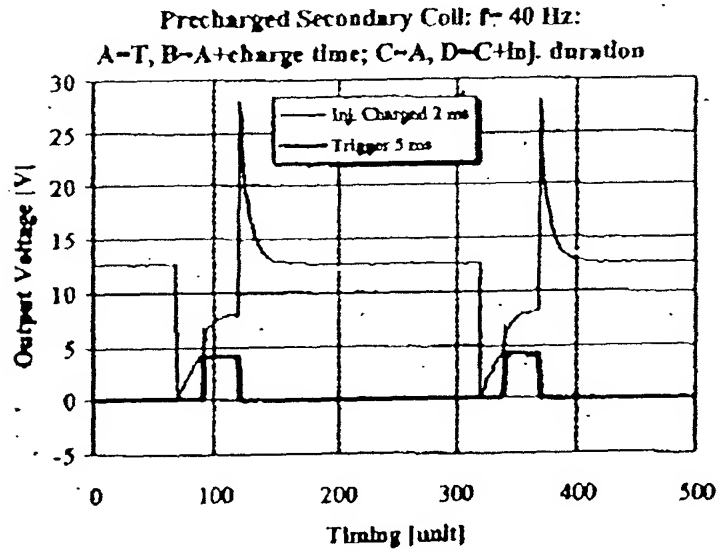
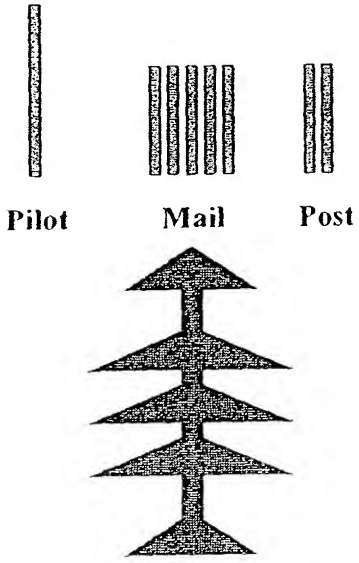


Fig. 12B



Stable Multiple
Ultra-Short Injection
(Target Technology)

Figure 13

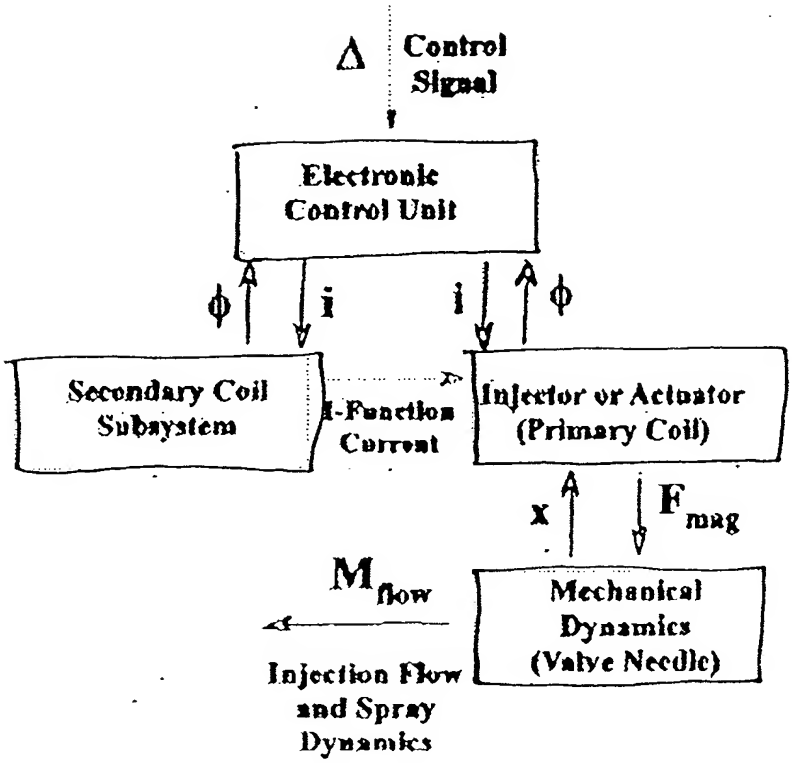

Δ
Control Signal
Electronic Control Unit
ϕ
i
i
ϕ
Secondary Coil Subsystem
i-Function Current
Injector or Actuator (Primary Coil)
x
F mag
M flow
Mechanical Dynamics (Valve Needle)
Injection Flow and Spray Dynamics

Figure 14

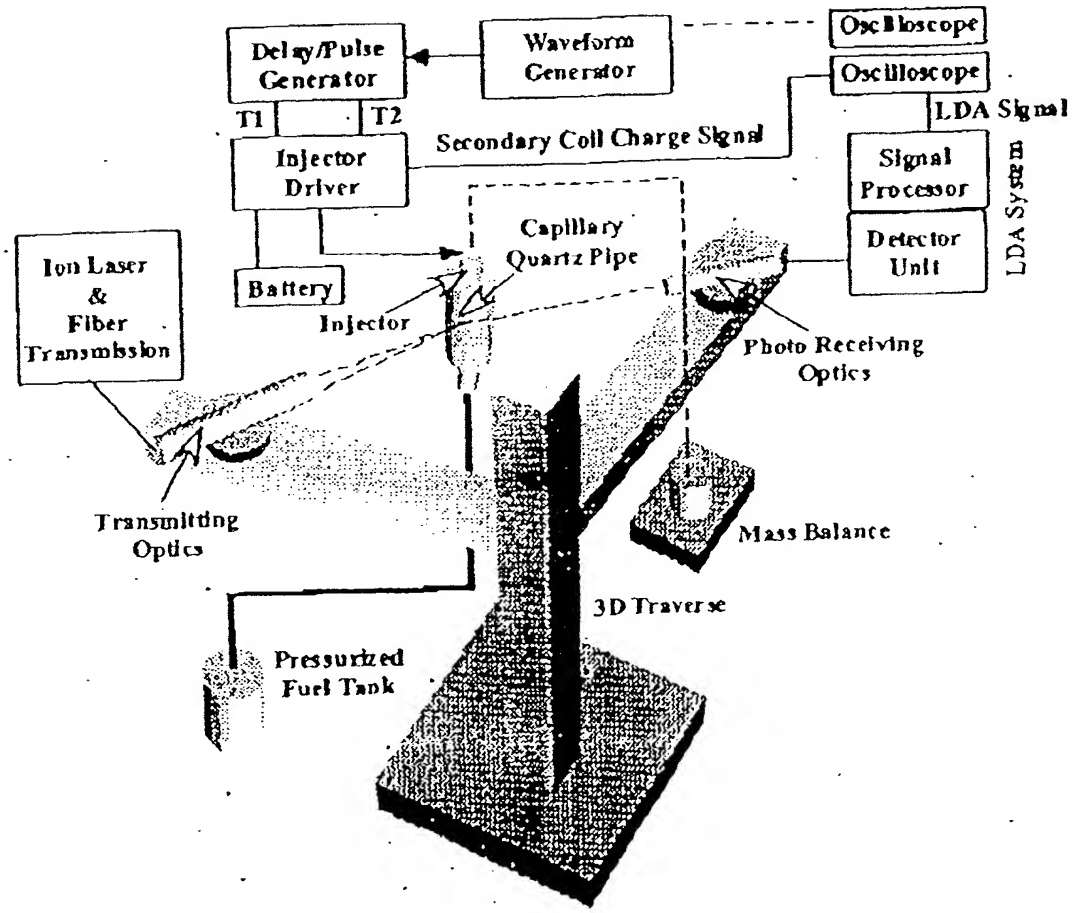

Delay/Pulse Generator
Waveform Generator
Oscilloscope
Oscilloscope
LDA Signal
T1
T2
Secondary Coil Charge Signal
Injector Driver
Signal Processor
LDA System
Capillary Quartz Pipe
Detector Unit
Ion Laser & Fiber Transmission
Battery
Injector
Photo Receiving Optics
Transmitting Optics
Mass Balance
3D Traverse
Pressurized Fuel Tank

Figure 15

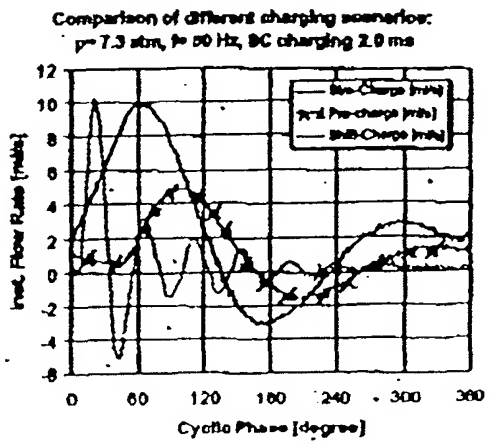


Fig. 16A

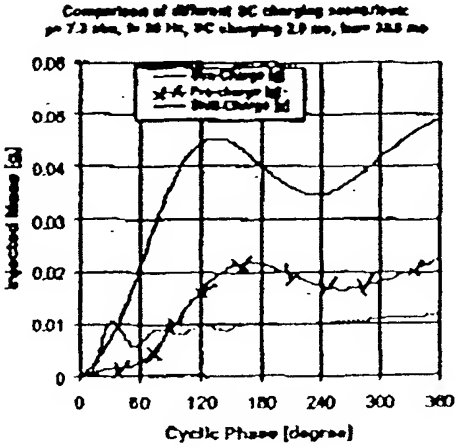


Fig. 16B

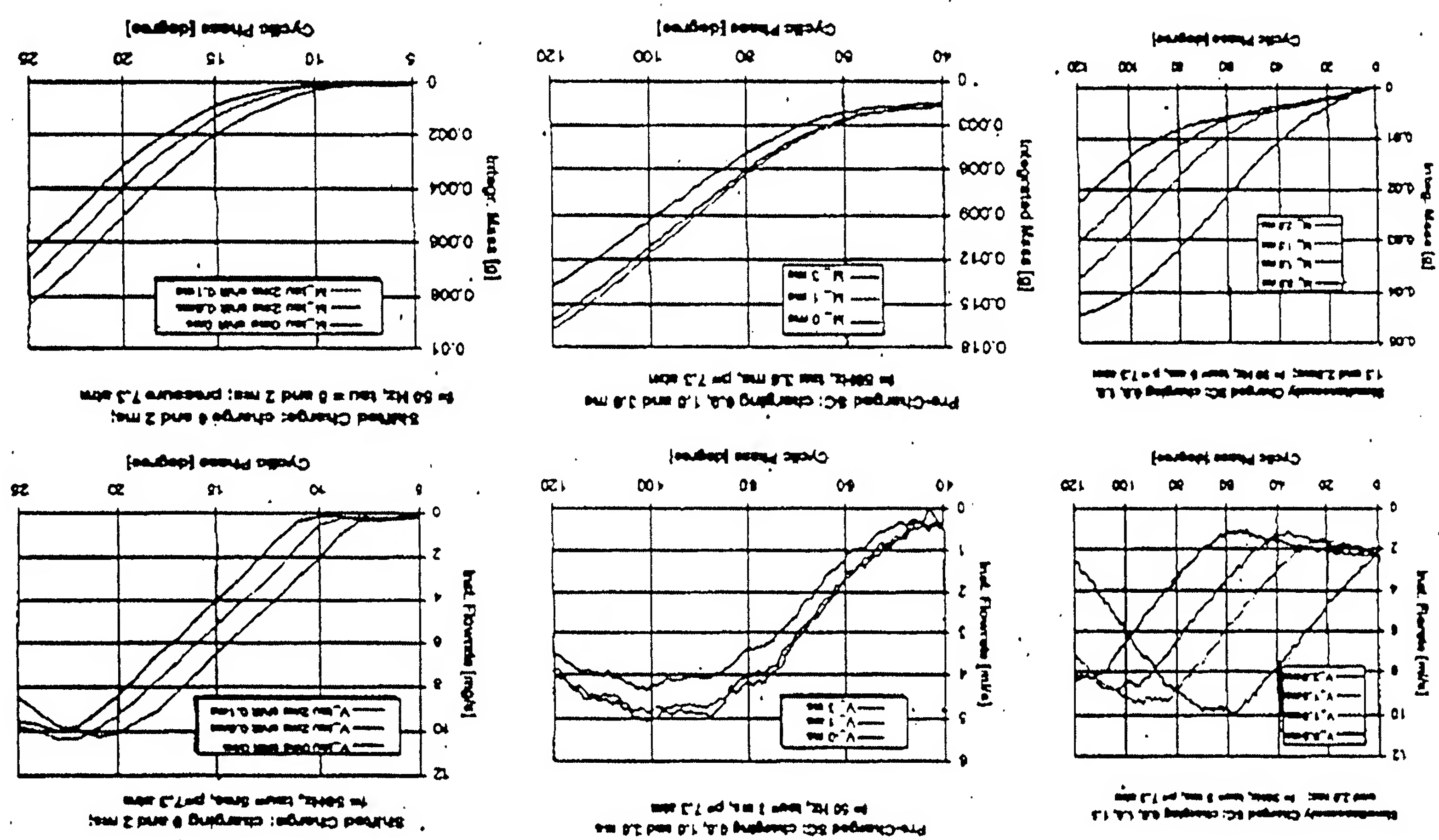


Figure 17

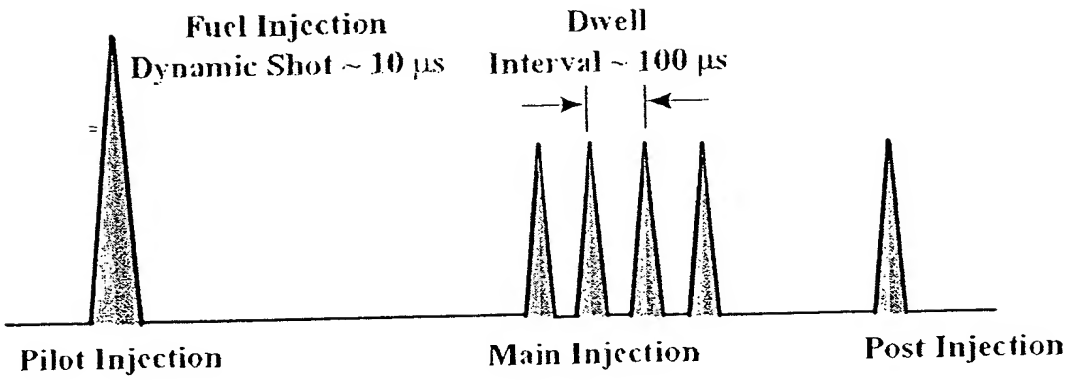

Fuel Injection
Dynamic Shot ~ 10 μs
Dwell
Interval ~ 100 μs
Pilot Injection
Main Injection
Post Injection

Figure 18

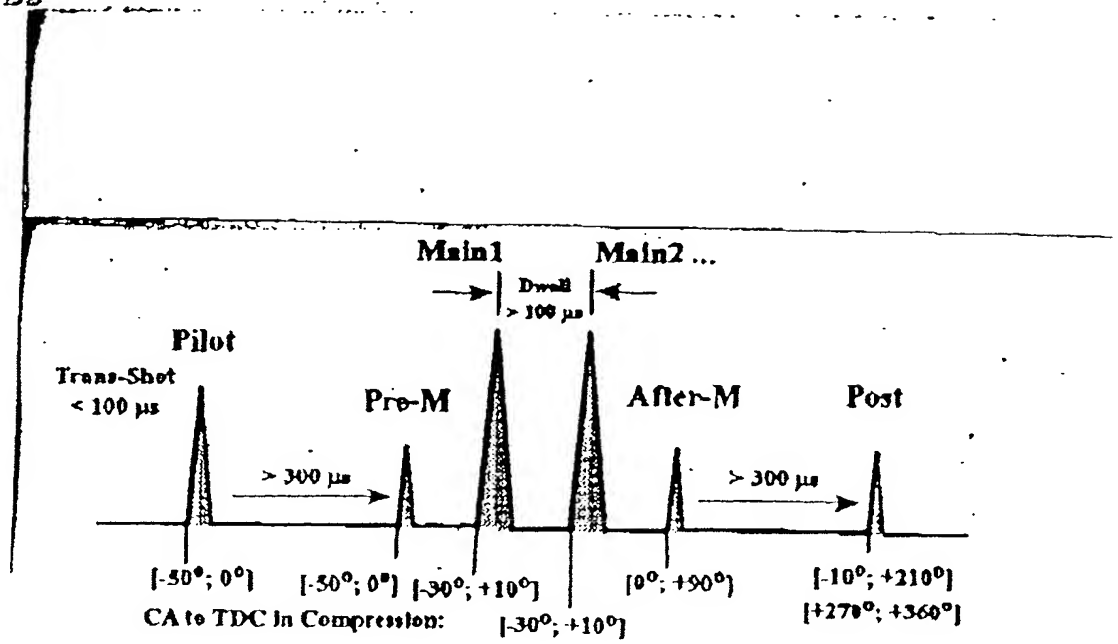

Main1
Main2 ...
Dwell
> 100 µs
Pilot
Trans-Shot
< 100 µs
Pre-M
After-M
Post
> 300 µs
> 300 µs
[-50°; 0°]
[-50°; 0°]
[-30°; +10°]
[0°; +90°]
[-10°; +210°]
[+270°; +360°]
CA to TDC in Compression:
[-30°; +10°]

Figure 19

#	Injector	L_mean µH min	L_mean µH max	R_mean Ω min	R_mean Ω max	Time L/R µsec averaged	ω21 Freq R/L kHz averaged	0.5*I²*L/T E_peak W I_p 18A	E_hold W I_h 12A	4*E_peak W	ω22=w21/2 R/L_22 kHz	T22=T21*2 T=L/R_22 µsec	L_22 µH I_p 18A	R_22 Ω R=L/T
	Bosch *Engine*													
1	I	65.73	65.75	0.45	0.45	146	6.85	72.9	4.7	291.6	3.42	292	526	1.80
2	II	76.24	76.35	0.35	0.45	191	5.24	64.8	5.5	259.2	2.62	381	610	1.60
3	III	68.48	68.41	0.35	0.45	171	5.84	64.8	4.9	259.2	2.92	342	548	1.60
3	IV	69.42	69.58	0.35	0.45	174	5.76	64.8	5.0	259.2	2.88	348	556	1.60
	addit:													
4	V	79.79	79.85	0.35	0.45	200	5.01	64.8	5.7	259.2	2.51	399	639	1.60
5	VI	84.75	84.84	0.35	0.45	212	4.72	64.8	6.1	259.2	2.36	424	678	1.60
6	VII	79.69	79.69	0.35	0.45	199	5.02	64.8	5.7	259.2	2.51	398	638	1.60

Figure 20

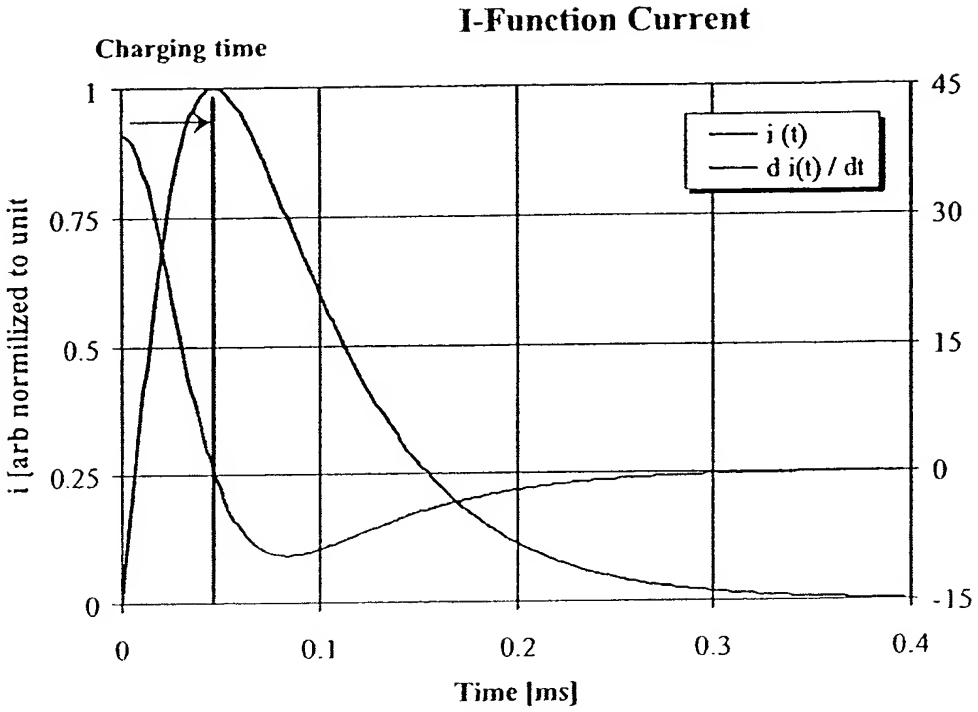
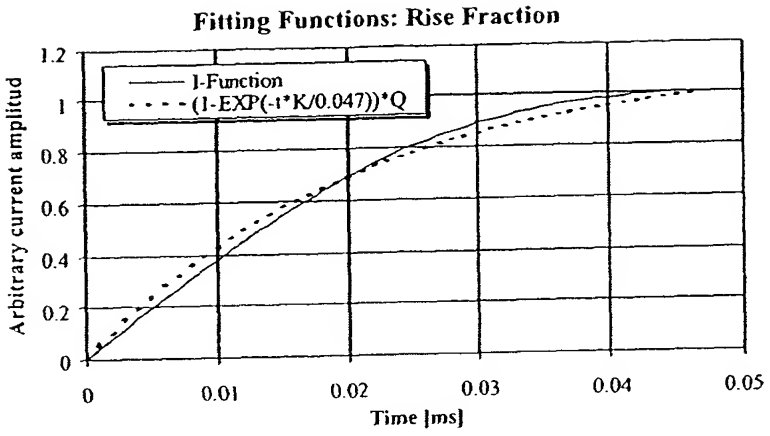

I-Function Current
Charging time
i [arb normilized to unit
1
0.75
0.5
0.25
0
45
30
15
0
-15
0
0.1
0.2
0.3
0.4
Time [ms]
i (t)
d i(t) / dt

Figure 21


Fitting Functions: Rise Fraction
I-Function
(1-EXP(-t*K/0.047))*Q
Arbitrary current amplitud
1.2
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
0.05
Time [ms]

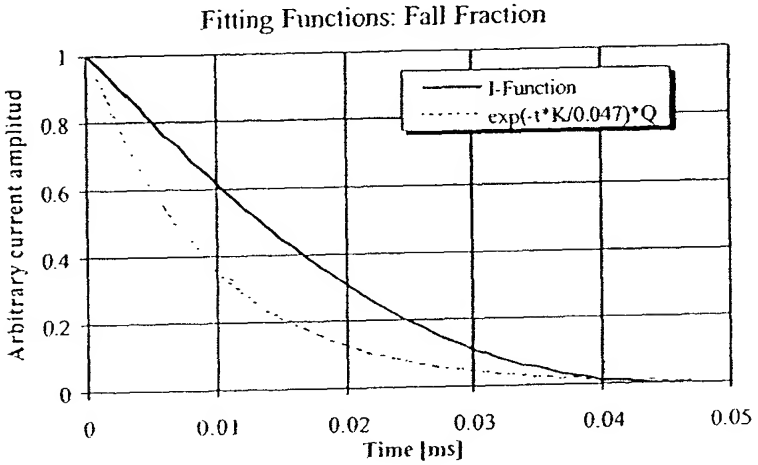

Fitting Functions: Fall Fraction
I-Function
exp(-t*K/0.047)*Q
Arbitrary current amplitud
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
0.05
Time [ms]

Figure 22

No.	Parameter	Calcul formula	Dimension	Value	Control	Device/Unit
1	Inductance	L, measured	µH	#REF!	L/R Meter IIB	Bosch injctor I
2	Resistance	R, measured	Ω	#REF!	Mutimeter	Bosch injctor I
3	T-Response	L/R	µs	#REF!	HP infinum scope 500 MHz, 1GSa/s	Bosch profile
4	F-Response	R/L	kHz	#REF!	HP infinum scope 500 MHz, 1GSa/s	Bosch profile
5	Cycle [Hz] 33.33	considered	degree ms pts	360 30.0 16000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
6	P Injection offset *"-X deg BTDC"*	considered START	degree ms pts	157.5 13.13 7000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
7	M Injection offset "TDC"	considered	degree ms pts	180 15.00 8000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
8	P_M interval	P_off - M_off X BTC	degree µs pts	22.5 1875 1000	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
9	Normal injection *"-X deg BTDC"*	max 2.2 ms	degree µs pts	26.4 2200 1173	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
10	P_duration= M_duration	considered	degree µs pts	7.2 600 320	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
11	P_M_dwell	(P_off - M_off)-P_dur	degree µs pts	15 1275 680	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM
12	Total Injection Duration	P_dur +dwell+M_d_off	degree µs pts	30 2475 1320	HP/Agilent 33120A 15 MHz wavegenerator	Injector solenoid PROGRAM

Figure 23

Scales	I [A]	2.0	t [ms]	0.200	T [pts]	16000	
	L [mm]	9.8	L [mm]	14.1	V_arb [-]	1	
	I/L [A/mm]	0.204	t/L [ms/mm]	0.01418	R [Ohm]	0.45	
					T [ms]	30.0	

first shot [us]	600	points	320					
second shot [us]	600	points	320	total pts	320	number of sine cycle	5	
dwell interval [us]	1275	points	680	exp_rise	9.36			
				exp_fall	9.60			

Profile MI_33_2x600_1275_SC	Phase	τ_lin [mm]	I_lin [mm]	τ_abs [ms]	I_abs [A]	τ_pts [-]	I_arb [-]	V_abs [V]	Δτ_pts [-]	ΔI_arb [-]	ΔV_abs [V]
τ_off [pts]											
7000	A	0.0	0.0	0.000	0.00	7000	0.000	0.000	0	0.000	0.000
157.5°	B	I-Function	First Peack	0.175	17.80	7093	1.000	8.010	93	1.000	8.010
FIRST SHOT	C	3.6	56.2	0.051	11.46	7121	0.644	5.159	27	-0.356	-2.851
	D	calculation	56.0	0.280	11.42	7270	0.642	5.141	149	-0.002	-0.018
	E	I-Function	0.0	0.094	0.00	7320	0.000	0.000	50	-0.642	-5.141
			total	0.600				total	320		
	CD_osc	4.5	2.8	0.128	0.57	61	0.032	0.257			
τ_off [pts]											
8000	A	0.0	0.0	0.000	0.00	8000	0.000	0.000	0	0.000	0.000
180°	B	I-Function	First Peack	0.175	17.80	8093	1.000	8.010	93	1.000	8.010
SECOND SHOT	C	3.6	56.2	0.051	11.46	8121	0.644	5.159	27	-0.356	-2.851
	D	calculation	56.0	0.280	11.42	8270	0.642	5.141	149	-0.002	-0.018
	E	I-Function	0.0	0.094	0.00	8320	0.000	0.000	50	-0.642	-5.141
								total	320		
	CD_osc	4.5	2.8	0.128	0.57	61	0.032	0.257			

Figure 24

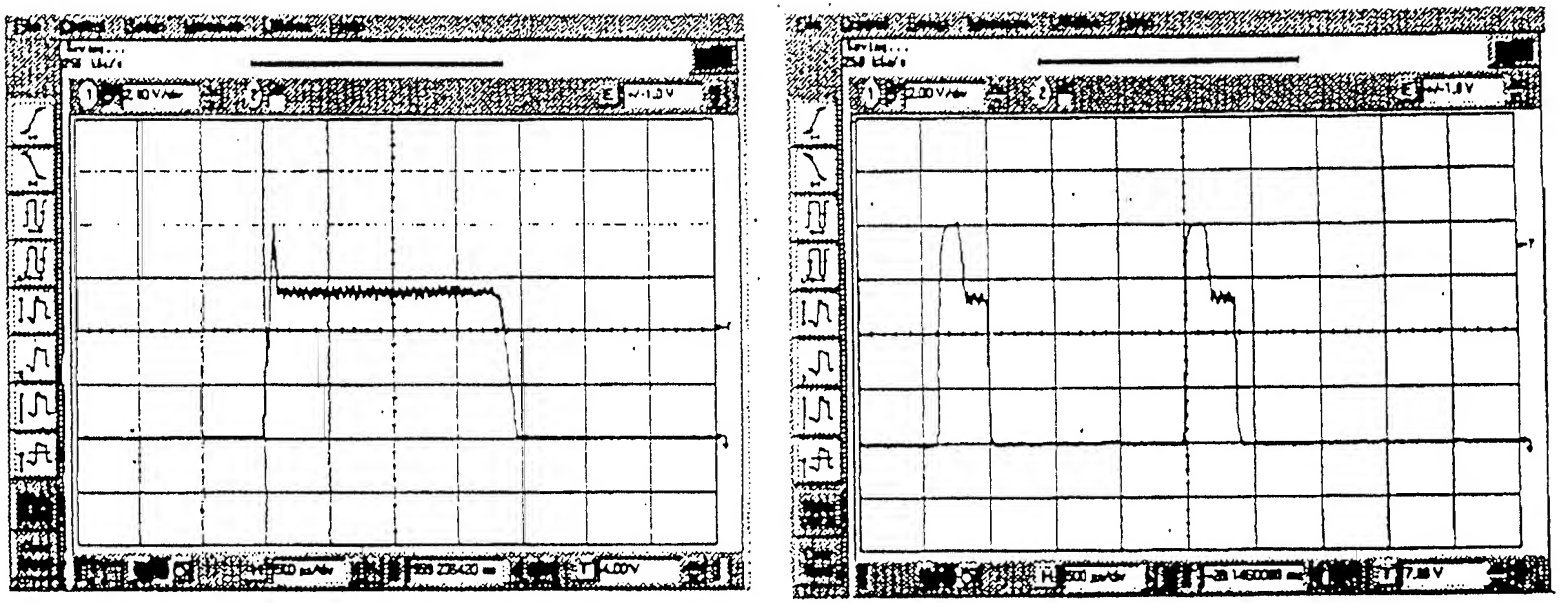
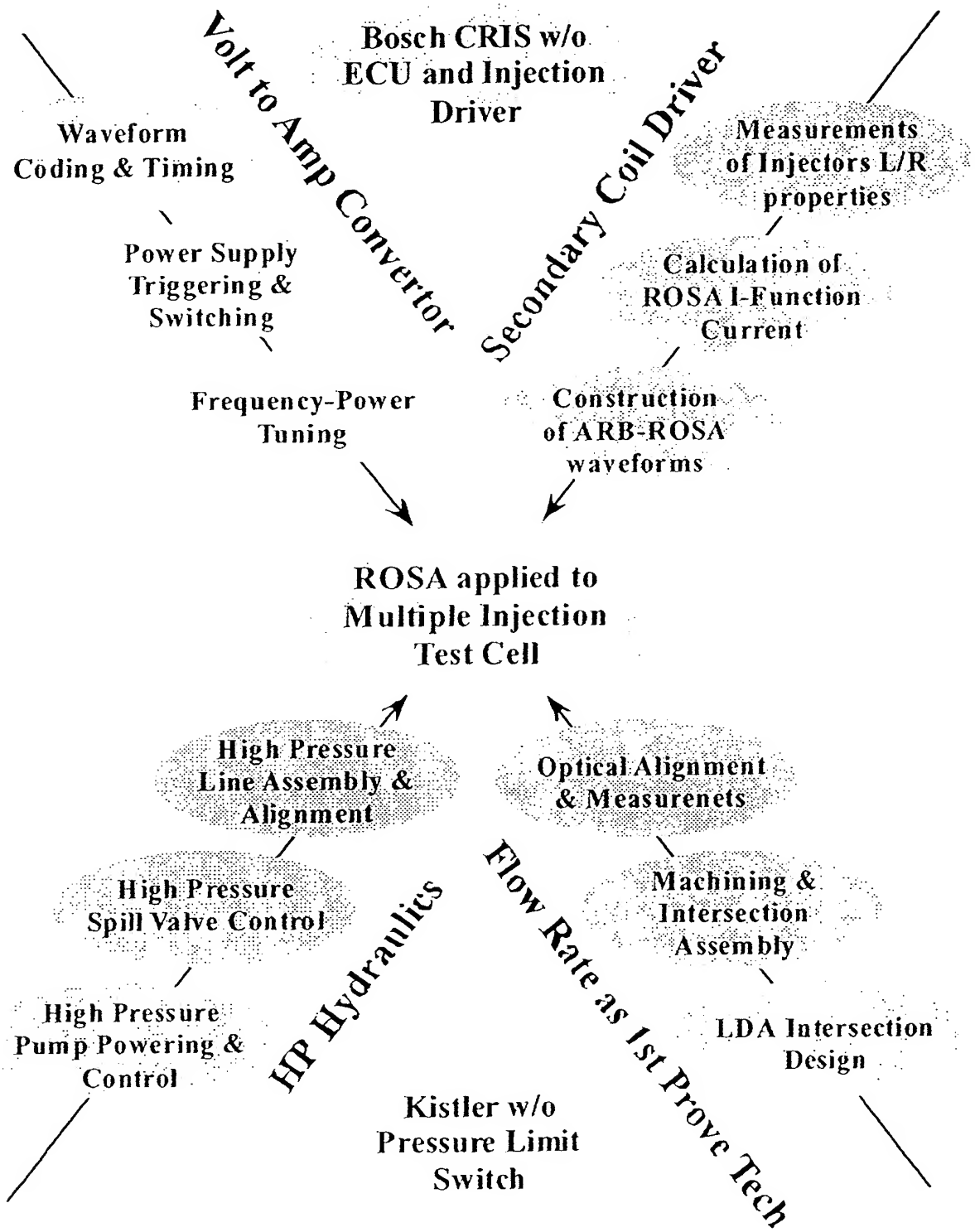


Figure 25

Figure 26

Controllable Multiple Injection System applied to Bosch Common Rail: Solution



Measurement Setup to Verify High Pressure Multiple Injection

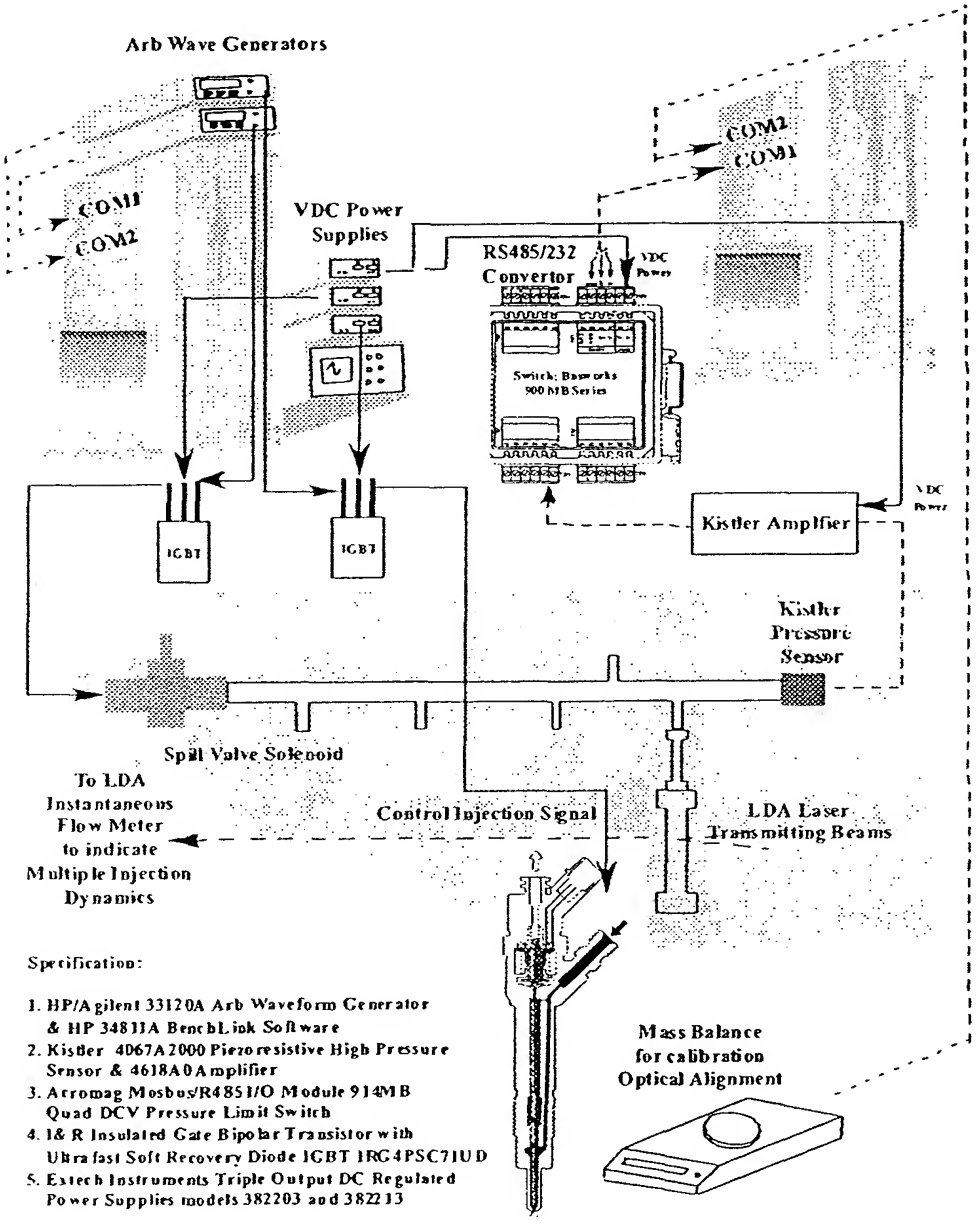
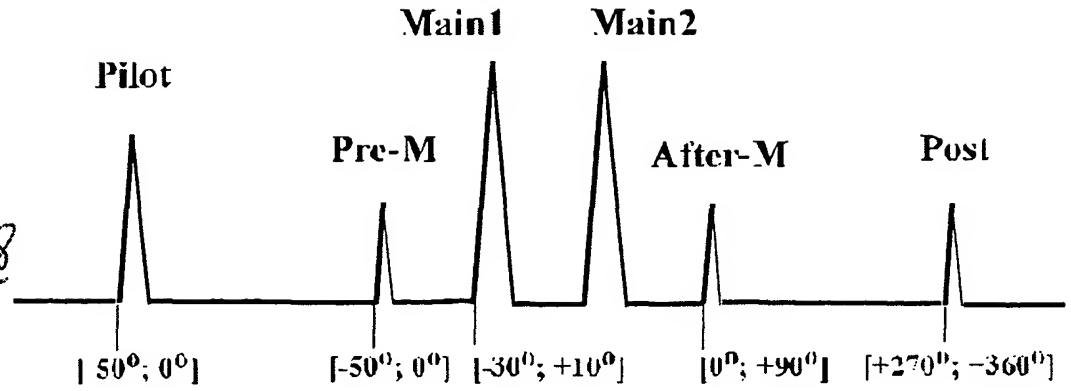


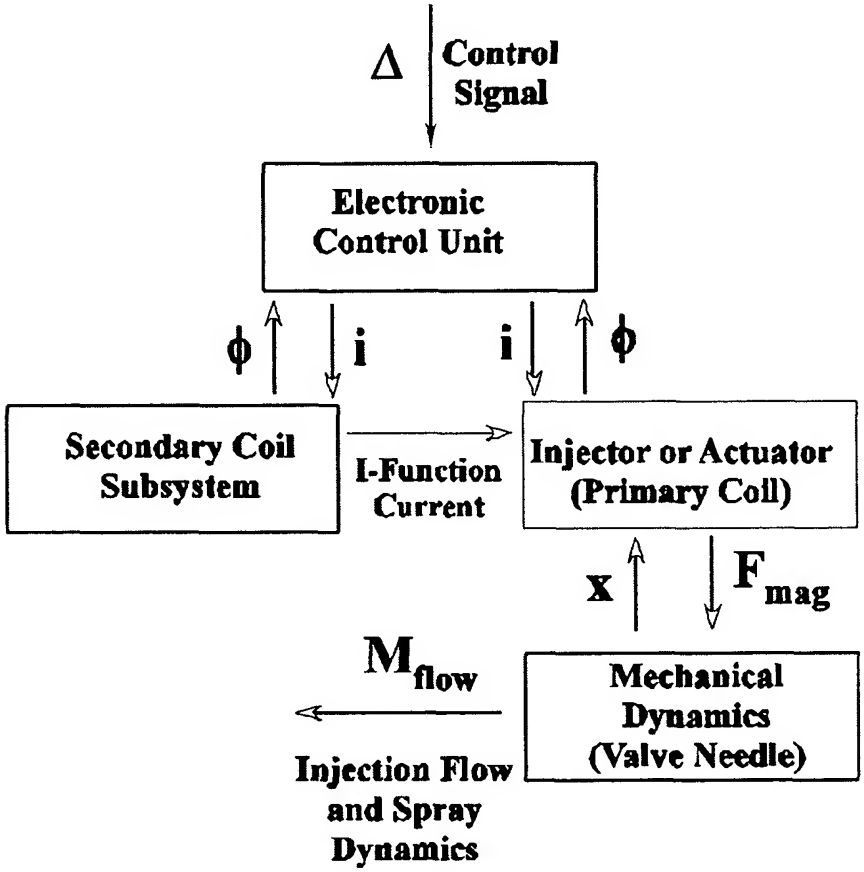
Figure 27

Fig. 28



Sketch to six-shot injection cycle along arbitrary referenced camshaft phases.

Fig. 29



Injection control test configuration used for verification of dynamic response: instantaneous flow rate upstream of injector and spray downstream of injector.

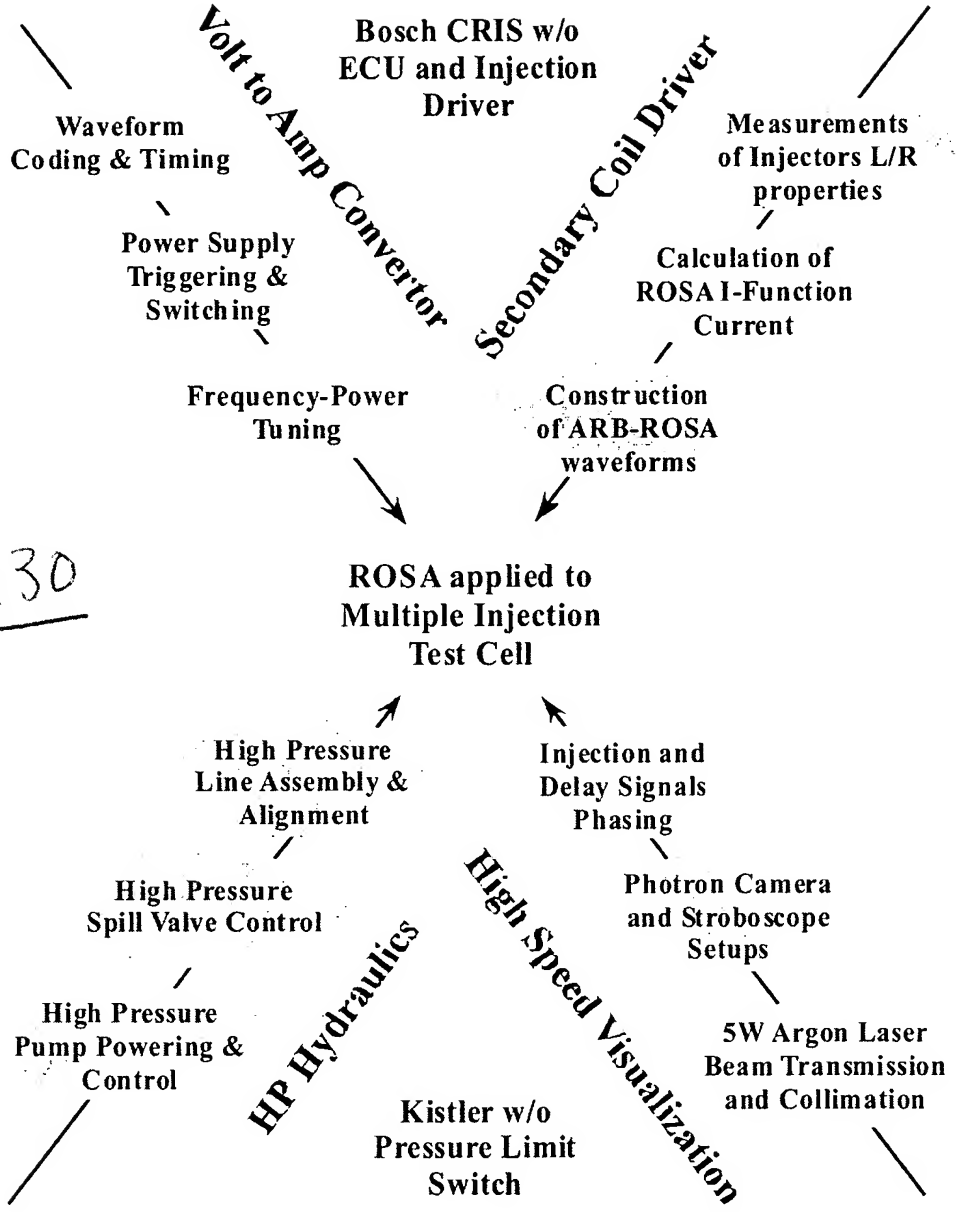
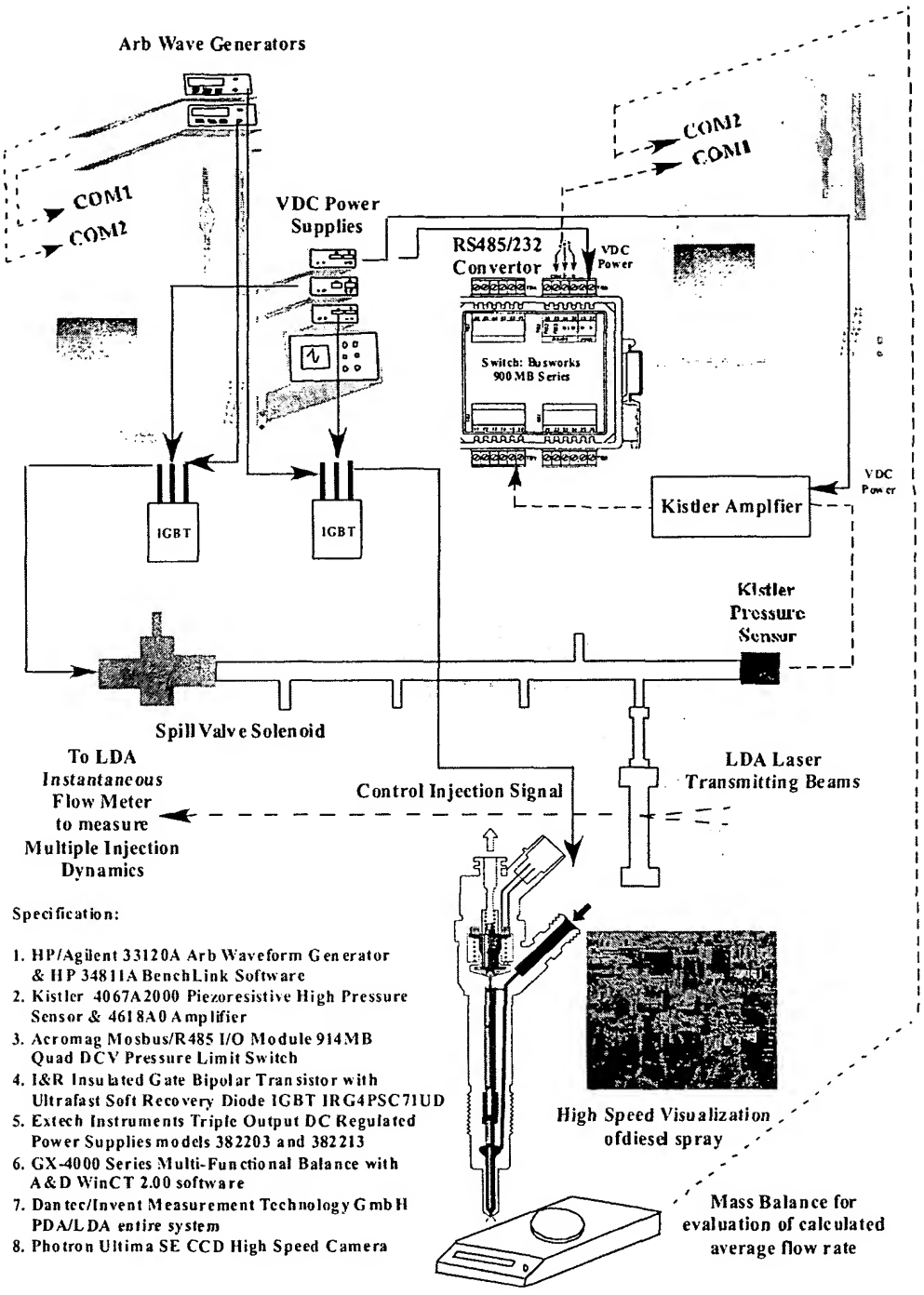


Fig. 30

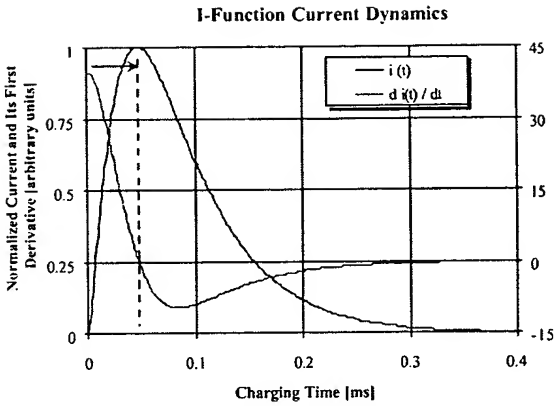
Initial available units of CRIS (grays) and algorithm for construction of ROSA multiple injection control systems.

Fig. 31



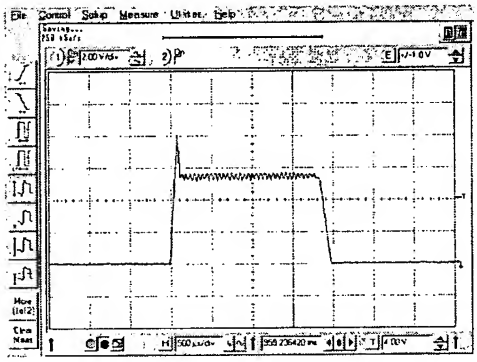
Integrated ROSA measurement configuration to visualize diesel spray by means of high-speed digital camera and quantify injection by means of instantaneous flow rate.

Fig. 32



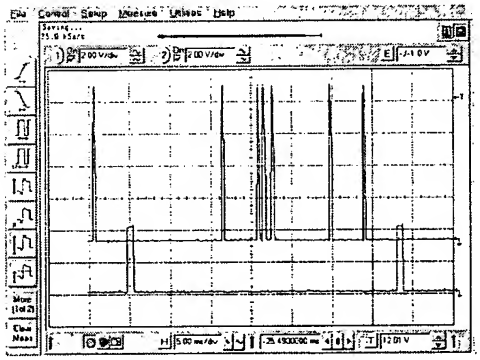
Arbitrary I-Function and its derivative.

Fig. 33



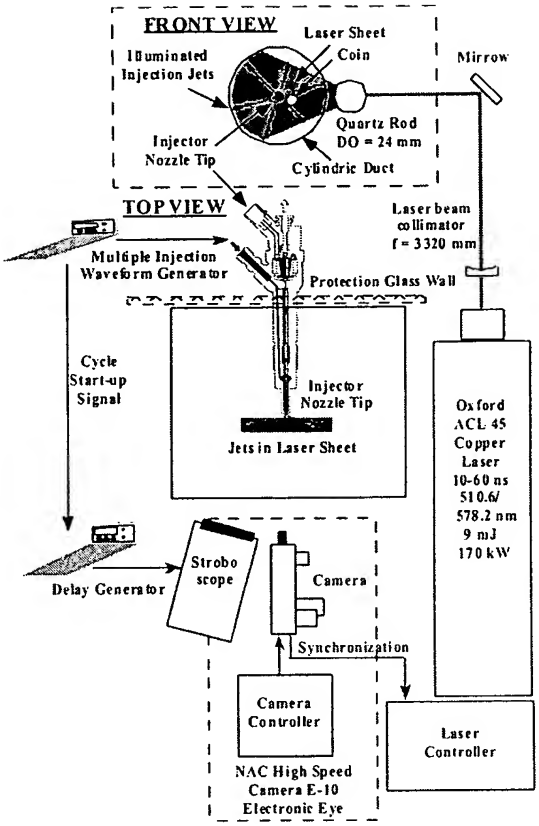
Arbitrary 2 ms Bosch injection.

Fig. 34

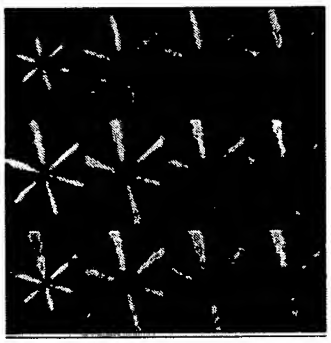


Arbitrary 6-shot injection and stroboscope (2nd channel) signals.

Fig. 35



Visualization at 5,000 fps.



Example of spray at low camera speed.

Fig. 36

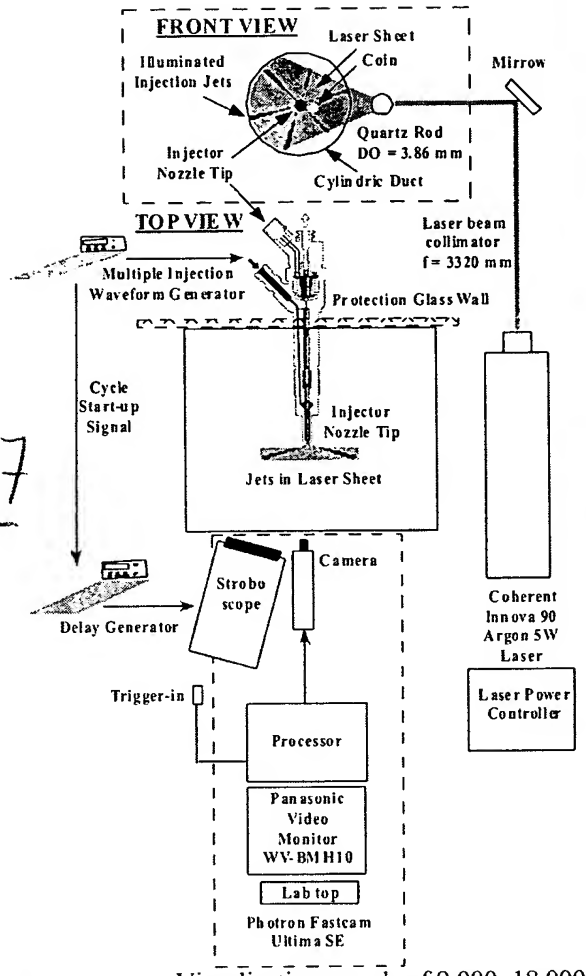
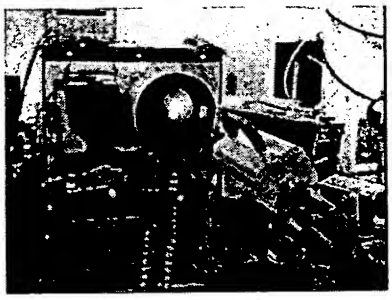
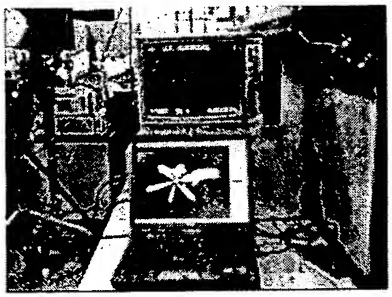


Fig. 37



A. Injector setup with stroboscope

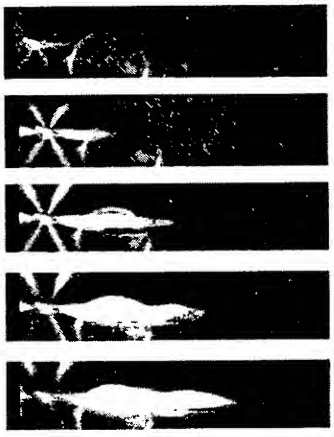


B. Signal processor with monitor

Fig. 38

Visualization optics setup, white disc is US quarter,

Visualization speeds of 9,000; 18,000; 27,000 and 40,500 fps



t = 0.126166 s

t = 0.126222 s

t = 0.126277 s

t = 0.126333 s

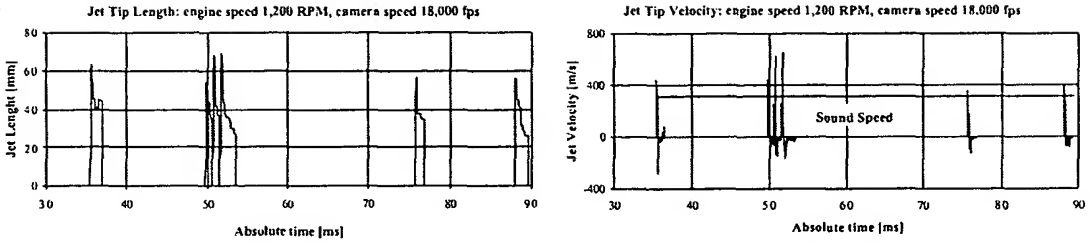
t = 0.126388 s

t = 0.126333 s

Fig. 39

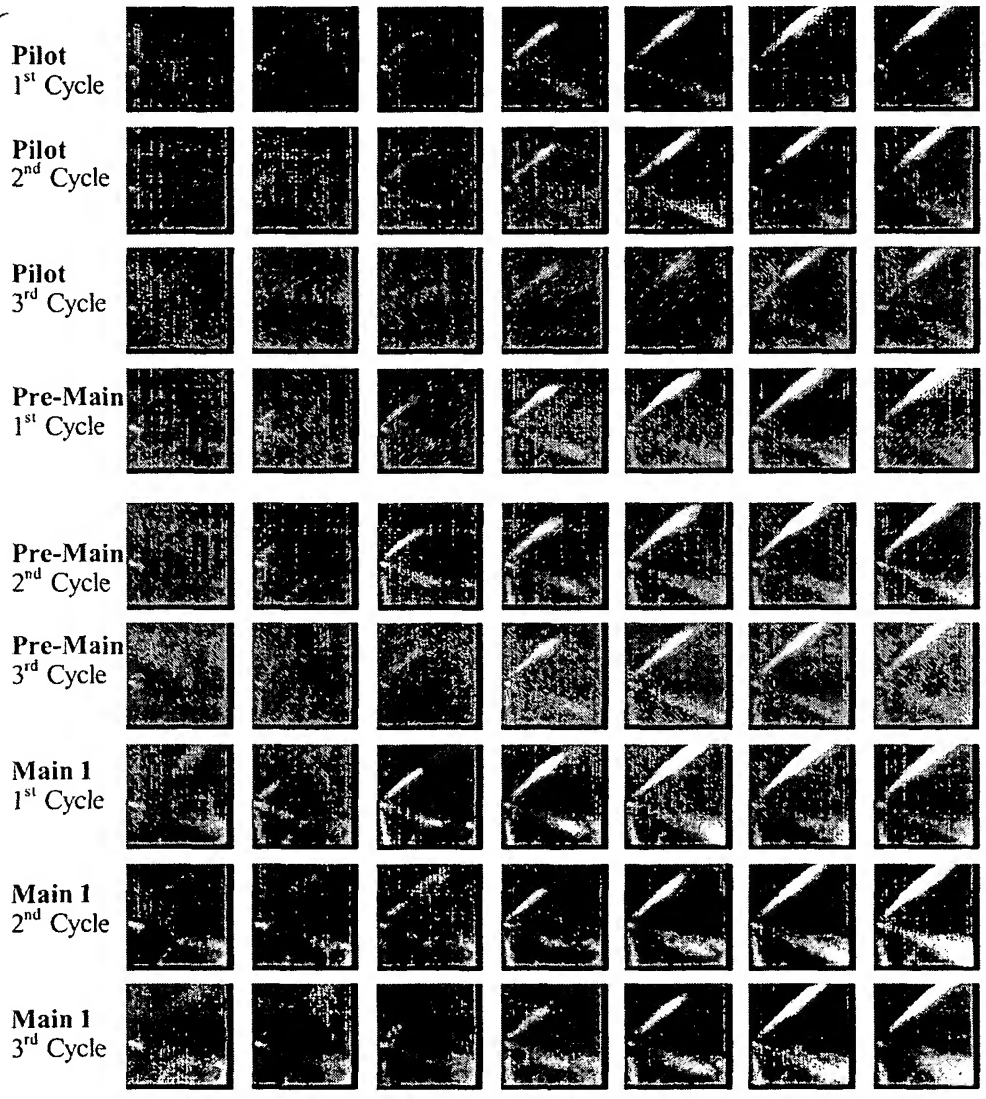
Pilot shot in six-shot injection: engine speed 2,400 RPM, frame duration 55.56 μs, coin size 24.76 mm.

Fig. 40



Liquid jet length and tip velocity for six-shot injection 100 ms cycle: at engine speed of 1,200 RPM and camera speed of 18,000 fps

Fig. 41



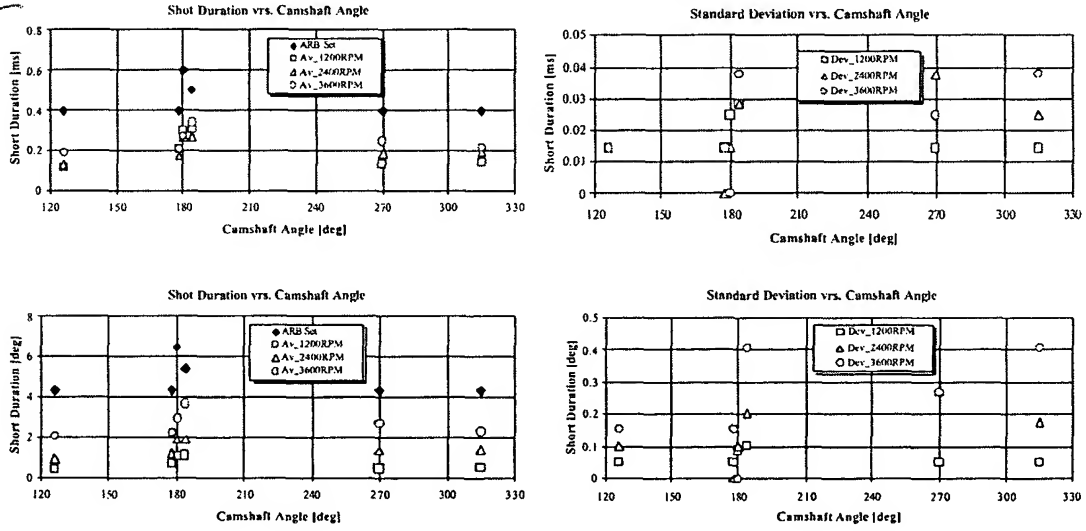
Cycle-to-cycle variability at resolution 24.69 μs/frame for 6-shot injection, only 4 shots are shown: engine speed 3,600 RMP, dwell between Pre-Main and Main 1 setup to 200 μs.

Fig. 42

Waveform Electronic Setup, Engine Speed 3,600 RPM								High Speed Camera Record at Speed of 40,500 fps							
	DURATION				PHASES				DURATION				PHASES			
		pts	ms	deg		pts	ms	deg	frames	ms	deg		frame	ms	deg
	period	16000	33.3	360	period	16000	33.33	360	1350	33.333	360	period	1350	33.333	360
3	Main	288	0.6	6.5		8000	16.667	180.0	11	0.272	2.9		1969	17.210	185.9
	dwell_1	96	0.2	2.2					21	0.518	5.6				
2	Pre_M	192	0.4	4.3		7712	16.067	173.5	8	0.198	2.1		1940	16.494	178.1
1	Pilot	192	0.4	4.3		5600	11.667	126.0	8	0.198	2.1		1762	12.099	130.7
	dwell_2	240	0.5	5.4					28	0.691	7.5				
4	Main_2	240	0.5	5.4		8528	17.767	191.9	14	0.346	3.7		2008	18.173	196.3
5	After_M	192	0.4	4.3		12000	25.000	270.0	9	0.222	2.4		2302	25.432	274.7
6	Post	192	0.4	4.3		14000	29.167	315.0	7	0.173	1.9		2472	29.630	320.0
					Pilot-to-Pre_M	1920	4.000	43.2				Pilot-to-Pre_M	170	4.198	45
					Pre_M-to-Main1	96	0.200	2.16				Pre_M-to-Main1	21	0.519	6
					Main1-to-Main2	240	0.500	5				Main1-to-Main2	28	0.691	7
					Main2-to-AfterM	3232	6.733	73				Main2-to-AfterM	280	6.914	75
					AfterM-to-Post	1808	3.767	41				AfterM-to-Post	161	3.975	43

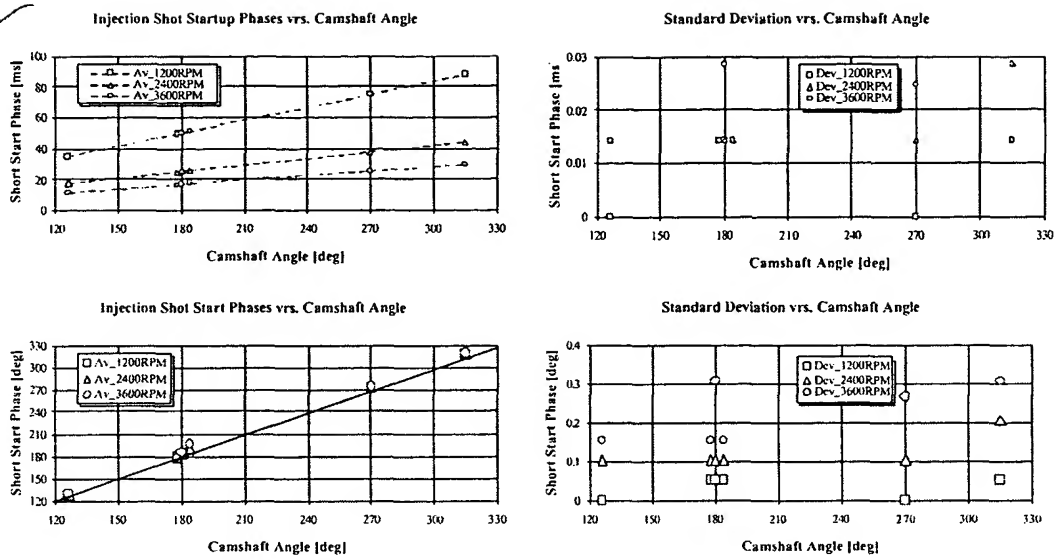
Comparison of dynamic injection timing (on the right) vs. waveform setups of timing (on the left): [pts] - points in ARB waveform generator, [ms] absolute time, [deg] – cam phasing, [frame] number of frames, 1 frame = 24.69 μs

Fig. 43



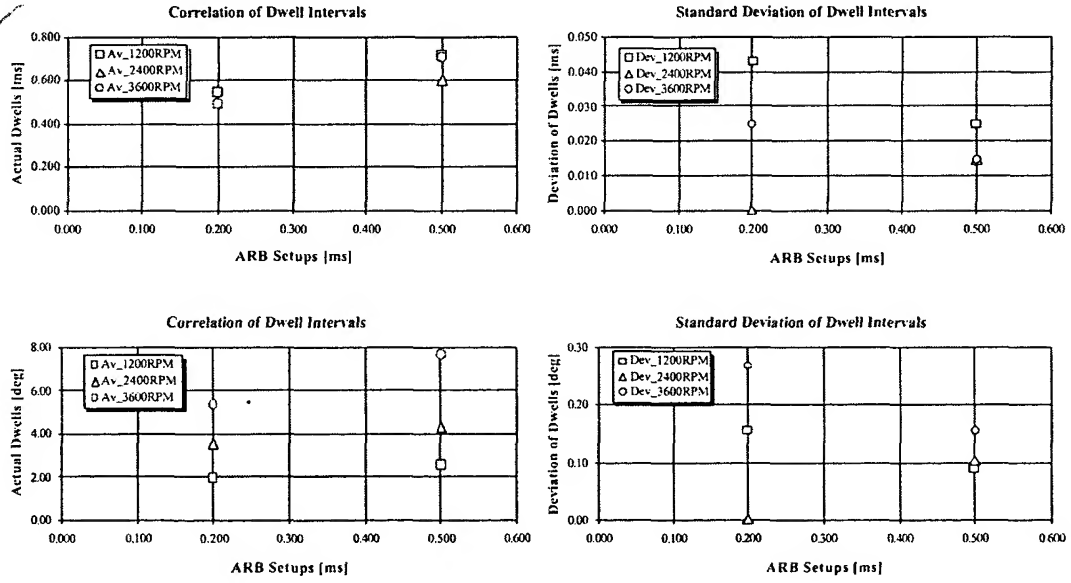
Pilot, Pre-Main, Main1, Main2, After-M, Post shots' duration and its standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).

Fig. 44



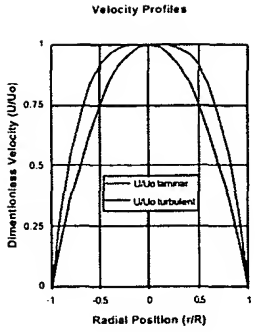
Pilot, Pre-Main, Main1, Main2, After-M, Post shots' startup phase and its standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).

Fig. 45



Dwell intervals between Pre-Main and Main1 (dwell 1), Main1 and Main2 (dwell 2) and their standard deviation in absolute time (2 top plots) and in camshaft angle (2 bottom plots).

Fig. 46



Velocity profiles for fully developed laminar and turbulent pipe flows.

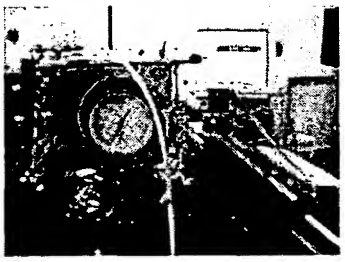
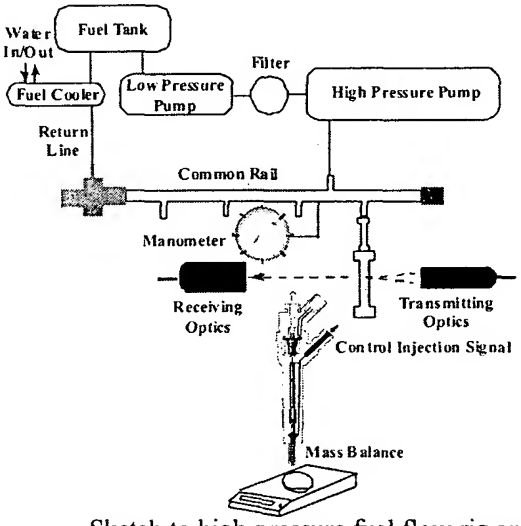


Fig. 49

LDA MI-2 cell withstanding high-pressures up to 2000 bar.

Fig. 47



Sketch to high-pressure fuel flow rig and LDA flow rate measurements.

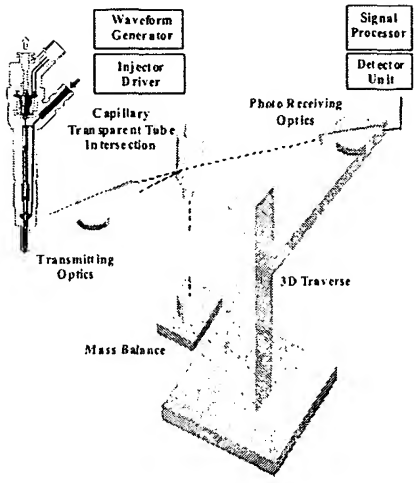
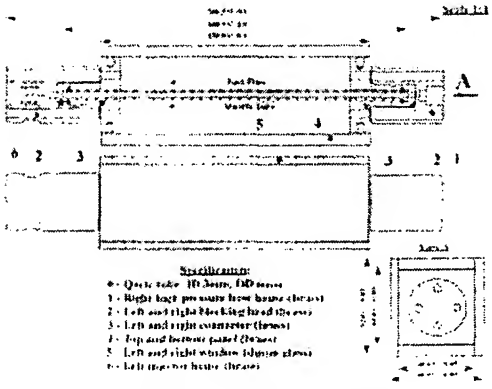


Fig. 50

LDA flow rate and mass balance.

Fig. 48



LDA MI-1 cell for injection pressures up to 140 bar

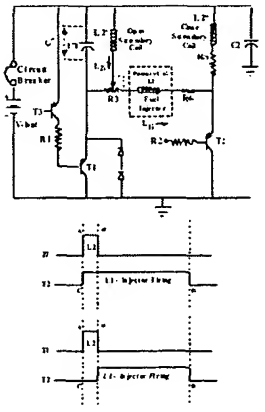
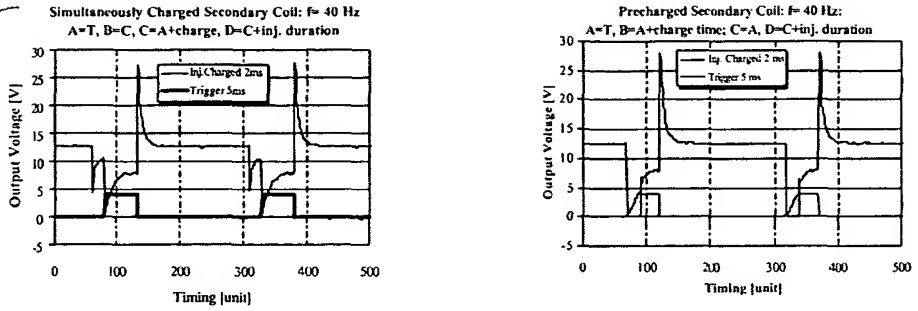


Fig. 51

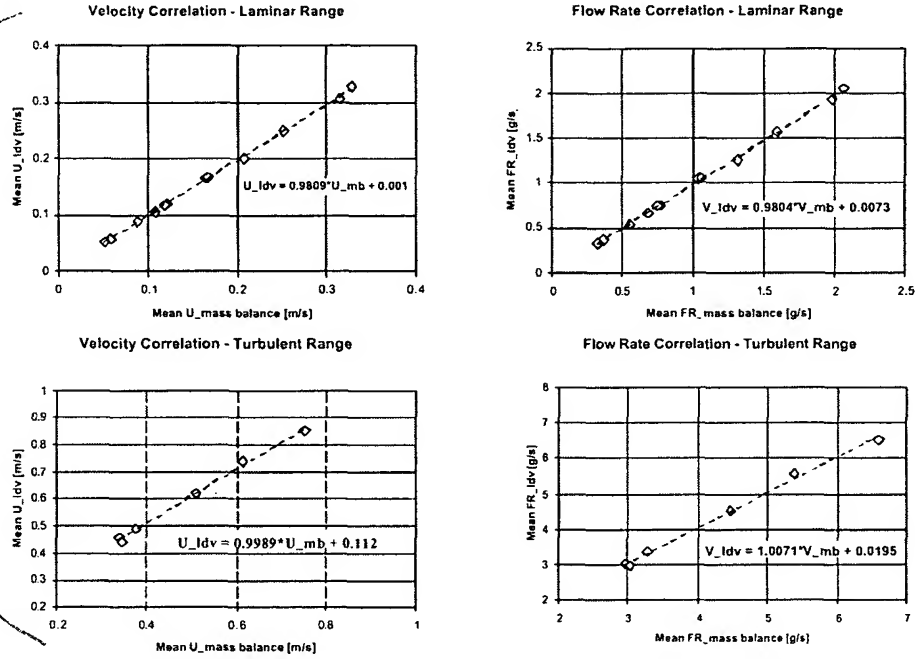
ROSA electronic circuit.

Fig. 52



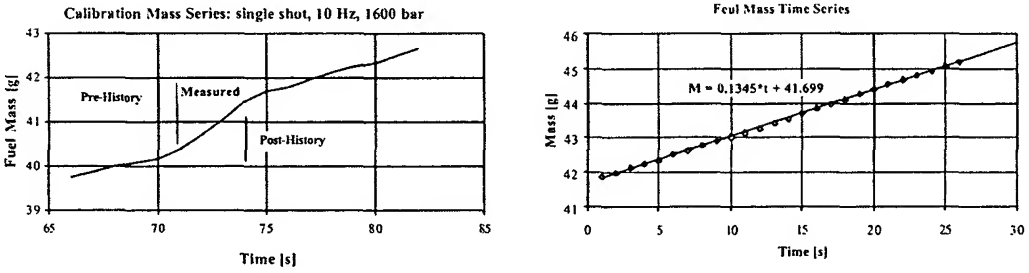
Simultaneous- and pre- charge; bold - injection duration (T2), thin - output from injector.

Fig. 53



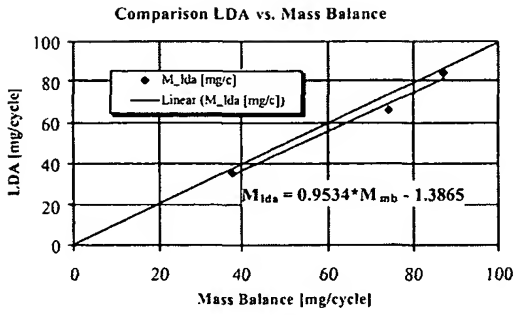
LDA calibration using mass balance measurements.

Fig. 54



ROSA-CRIS diesel injection: mass balance trace including "pre-history", "measured" and "post-history" injection parts.

Fig. 55



ROSA-CRIS diesel injection: fuel mass injected per cycle.

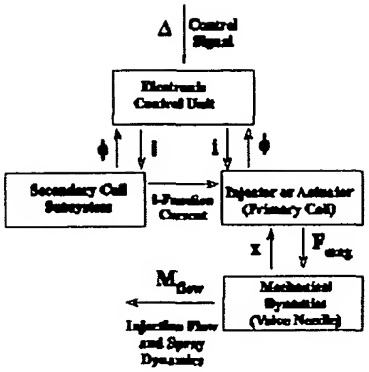
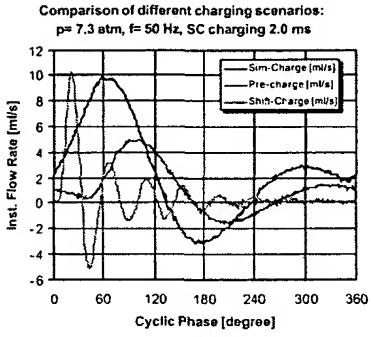
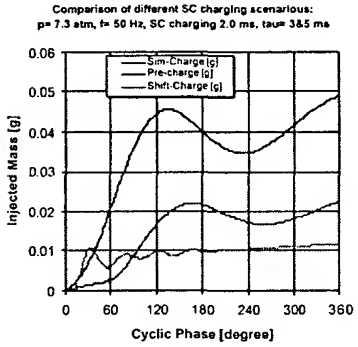


Fig. 56

Test configuration for verification of injection dynamics.

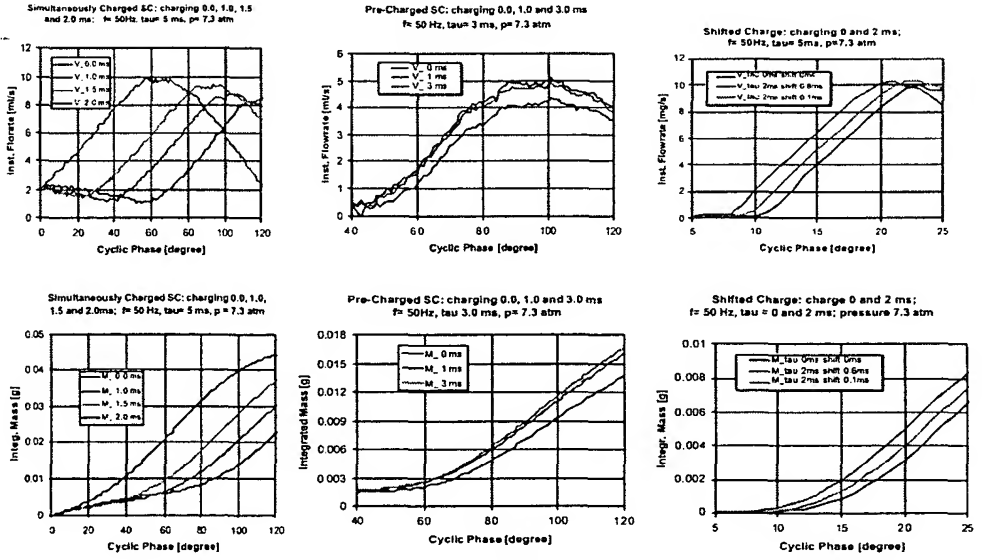
Fig. 57





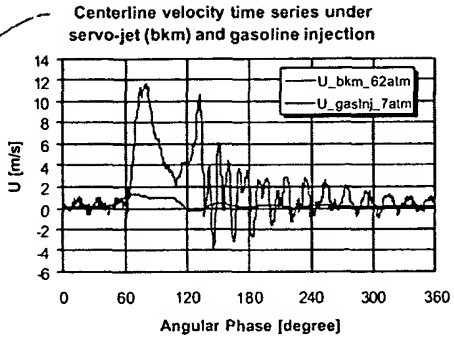
Comparison of different SC charging scenarios at the same injection condition: instantaneous volumetric flow rate and integrated injection mass.

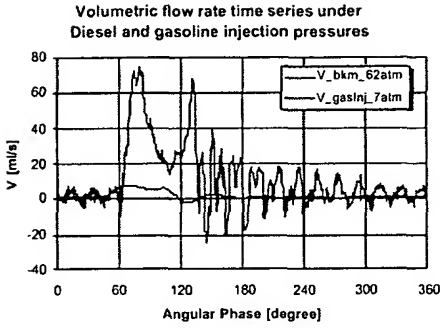
Fig. 58



Flow rate (top row) and integrated mass (bottom row) obtained for: simultaneous charge – 1st column, pre-charge – 2nd column, tuned charge – 3rd column

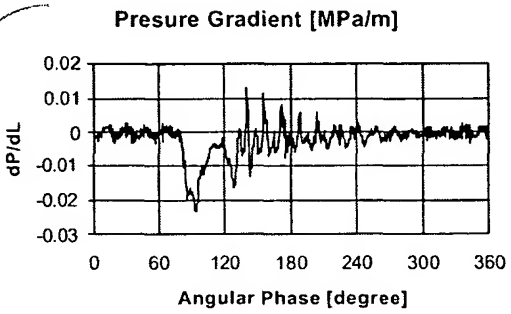
Fig. 59

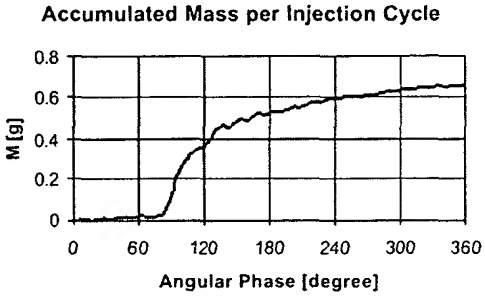




Velocity and flow rate: injection pressures - 62 (servo-jet) and 7 bar (gasoline).

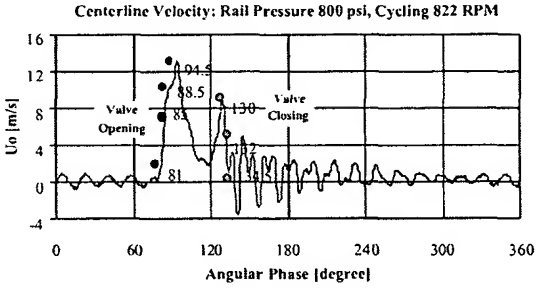
Fig. 60

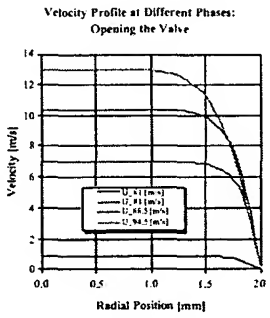


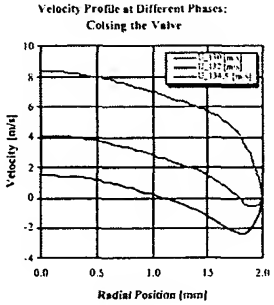


Pressure gradient and accumulated mass: p= 62 bar, f= 11 Hz, duration 15 ms.

Fig. 61







Velocity time series with selected angular phases (top) and velocity profiles for two stages: opening (bottom left) and closing (bottom right) of injector valve.

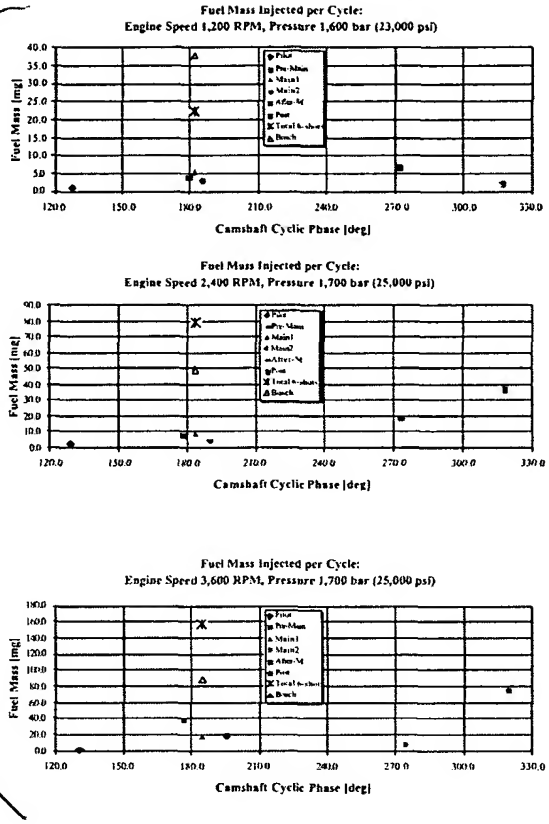


Fig. 62

Fuel masses for 6-shot injection and Bosch 1 ms single shot injection.

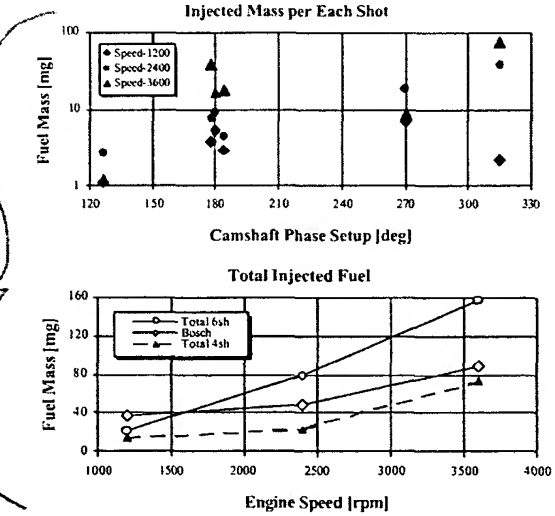


Fig. 63

Summary to dynamic of 6-shot injection and integrated fuel mass.

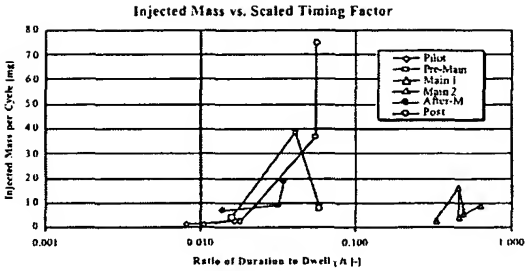


Fig. 64

Separation of low and high frequency domains by scaling timing factor τ / t

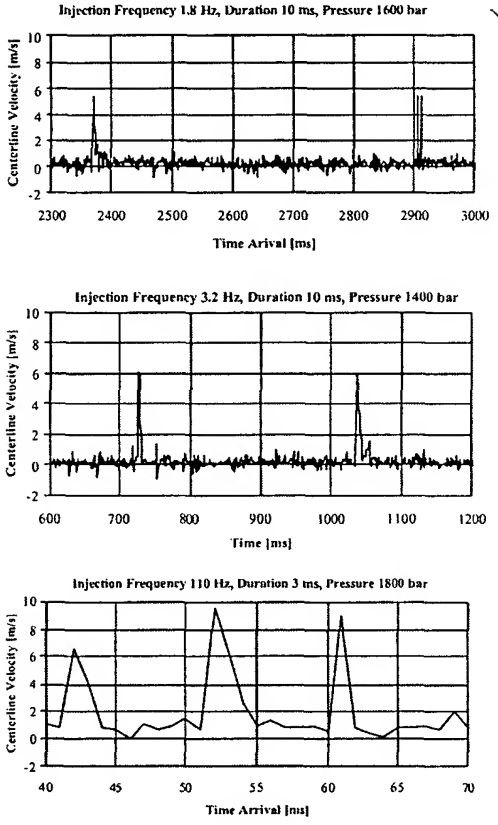
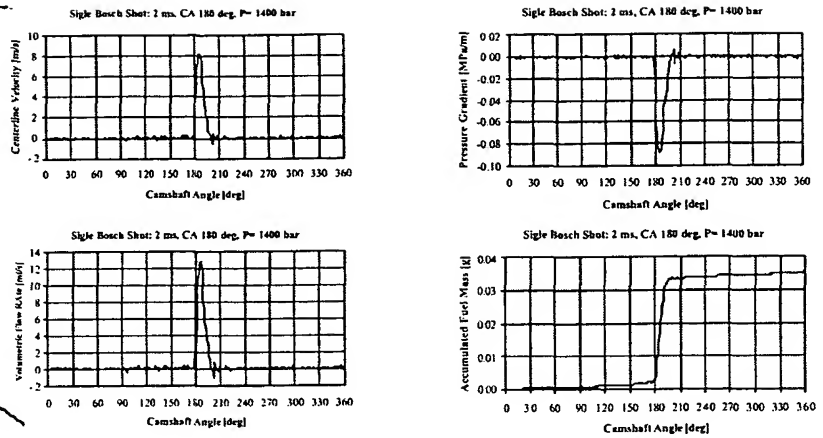


Fig. 65

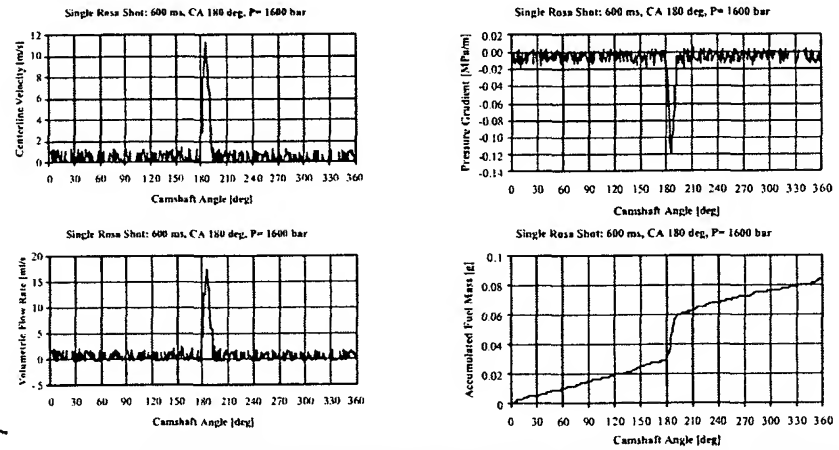
Examples of LDA time arrival series. data rates: top – 2.964 , mid – 2.641, bottom – 0.051 kHz.

Fig. 66



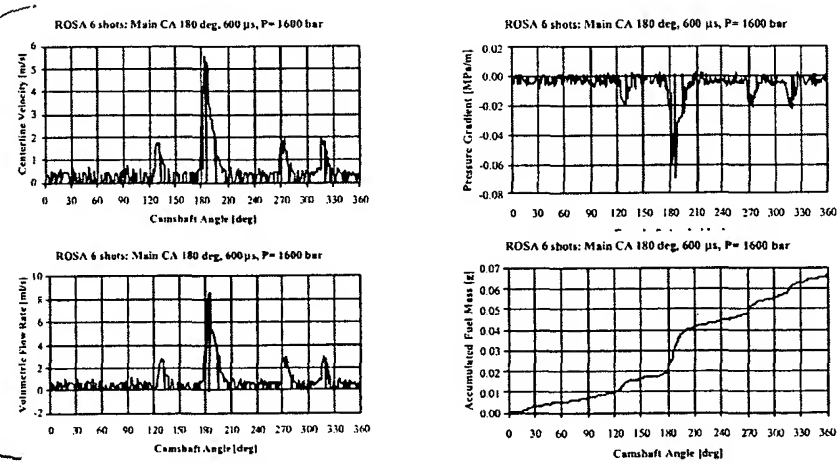
2-ms single reference injection: SOI at 180^0, p= 1400 bar.

Fig. 67



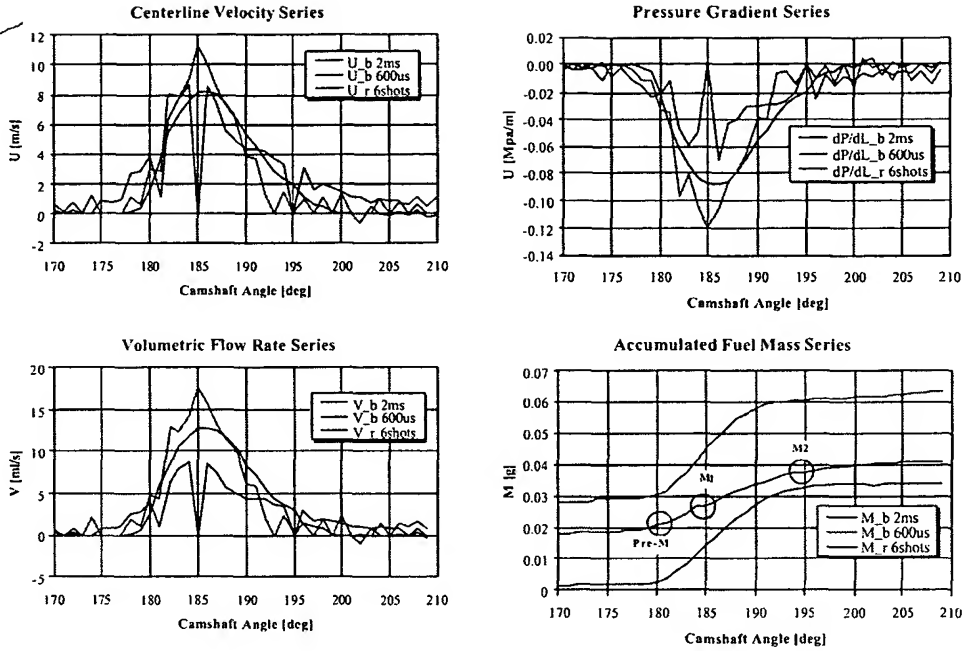
ROSA-controlled single shot injection: SOI at 180^0, p= 1600 bar.

Fig. 68



ROSA-controlled six shots injection: Main1 SOI at 180^0, p= 1600 bar.

Fig. 69



Comparison of dynamics for 2-ms reference single injection, p= 1400 bar and ROSA-controlled six shots injection, p= 1600 bar.

Fig. 70

	shot/pass	Start deg	End deg	duration ms	masses mg	% of total %
1	deliver 1	0	125	34.72	10.74	14.8
2	**Pilot**	125	133	2.22	4.18	5.8
3	deliver 2	133	175	11.67	4.33	6.0
4	**Pre-Main**	175	182	1.94	4.47	6.2
5	**Main 1**	182	186	1.11	7.30	10.1
6	**Main 2**	186	196	2.78	11.65	16.1
7	deliver 3	196	269	20.28	10.62	14.7
8	**After-M**	269	281	3.33	5.81	8.0
9	deliver 4	281	315	9.44	5.02	6.9
10	**Post**	315	327	3.33	4.76	6.6
11	deliver 5	327	360	9.17	3.54	4.9
	Total:				**72.42**	**100.0**
	injected				**38.17**	**52.7**
	deliver				**34.25**	**47.3**

Integrated Masses per Active and Passive (deliver) Injection Events.